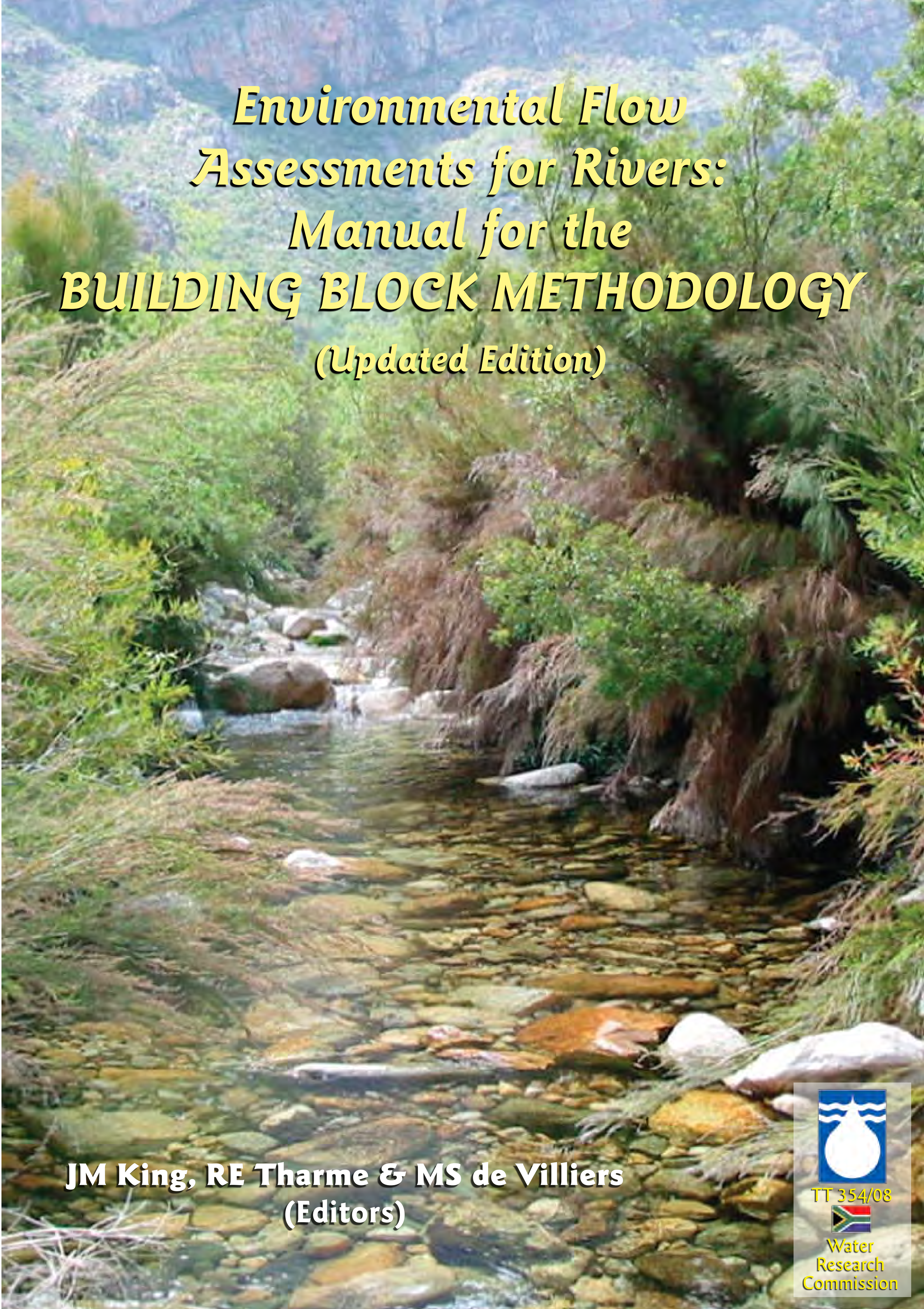

Environmental Flow Assessments for Rivers: Manual for the BUILDING BLOCK METHODOLOGY

(Updated Edition)

JM King, RE Tharme & MS de Villiers
(Editors)

TT 354/08

Water
Research
Commission

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Report to the
Water Research Commission

by

Freshwater Research Unit
University of Cape Town

WRC Report No TT 354/08
August 2008

Obtainable from:

Water Research Commission
Private Bag X03
Gezina
0031

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The publication of this report emanates from a project entitled *Technology Transfer of the Building Block Methodology for Instream Flow Assessments* (WRC Project No. K5/874).

This report was first published under the same title in 2000 as WRC Report TT 131/00. This updated version was edited by **CL MALAN** and is published as WRC Report TT 354/08.

ISBN 978-1-77005-721-0
Printed in the Republic of South Africa

Cover photo by Karl Reinecke

EXECUTIVE SUMMARY

Environmental (or instream) flows are flows that are left in, or released into, a river system with the specific purpose of managing some aspect of its condition. Their purpose could be as general as maintenance of a 'healthy' riverine ecosystem, or as specific as enhancing the survival chances of a threatened fish species. They could be targeting the river channel and its surface waters, groundwater, the estuary, linked wetlands or floodplains, the riparian zone, and/or any of the plant and animal species associated with any of these system components.

As the condition of river systems deteriorates globally, environmental flows are increasingly appearing on national and international political agendas, and the requirement to use them, in legislation. The science of advising on environmental flows is relatively young (about 50 years), but more than 100 methodologies and methods now exist for such assessments and at least 30 countries are using them routinely in water resource management, with the number growing annually.

South Africa formally addressed the topic in the 1980s, and during the 1990s made considerable progress at a national level. Tharme & King (1998) track the major milestones of this course. Recognising that international approaches to environmental flow assessments did not meet South Africa's needs entirely, development of a local approach was initiated. First introduced in a workshop for the Lephalala River in February 1992, what was to become the Building Block Methodology (BBM) was developed through application in a series of real water-resource development projects. The South African Department of Water Affairs and Forestry (DWAF) organised and partially funded the workshops, and the Water Research Commission (WRC) funded many of the river scientists who stepped forward to become involved, via their research projects. Through a decade of extraordinary cooperation and willingness to contribute, the national body of aquatic scientists, water managers and engineers developed the BBM to the point where it is now one of only a few advanced environmental flow methodologies in the world with a formal manual.

In addition, the BBM has advanced the field of environmental flow assessment in an entirely new direction, being a holistic methodology that addresses the health (structure and functioning) of all components of the riverine ecosystem, rather than focusing on selected species as do many similarly resource-intensive international methodologies. This kind of approach has been spearheaded in South Africa and Australia, in close collaboration, and because of its pragmatic and all-encompassing nature, has triggered exceptional growth in communication between many scientific disciplines, and between scientists and water managers.

During the 1990s, more than 15 BBM Workshops were held for different local rivers, as well as for the Logan River in Australia in 1996. The 1994 workshop for the Luvuvhu River was generally seen as the one in which the BBM 'came together', providing a sound template for further development of the methodology. The 1996 workshop for the Sabie-Sand River System brought together the developers of the BBM and members of the Kruger National Park Rivers Research Programme, in the most data rich application of the BBM to that date. A member of DWAF's Water Law Review Team attended the Sabie-Sand workshop, to assess whether or not the BBM could meet legal requirements in terms of quantifying the water required for river maintenance. As a result, an environmental flow allocation for maintaining river ecosystems was entrenched in South Africa's new National Water Act (No. 36 of 1998) as the ecological Reserve. This is one of the two components of the Reserve, the other being an allocation for basic human needs. Within the framework of Resource Directed Measures for Protection of Water Resources, established by DWAF, assessment of the Reserve is now being done for every major water body within South Africa. For various kinds of water-resource developments, Reserve determinations may be done at different levels of assessment, namely Desktop, Rapid, Intermediate or Comprehensive. Requirements for Comprehensive Reserve determinations were established based on the BBM, and it is currently the methodology used in such environmental flow assessments.

The BBM is essentially a prescriptive approach, designed to construct a flow regime for maintaining a river in a predetermined condition. This manual describes its basic nature and main activities, and provides guidelines for its application. It also introduces the links between the methodology and the procedures for determination of the ecological Reserve as embodied in the Water Act. The BBM has further provided the impetus for the evolution of several alternative holistic environmental flow methodologies, notably the Downstream Response to Imposed Flow Transformations (DRIFT) methodology. The DRIFT methodology is an interactive, scenario-based approach, designed for use in negotiations, and contains a strong socio-economic component, important when quantifying subsistence use of river resources by riparian peoples.

Reference:

THARME, R.E. & KING, J.M. 1998. Development of the Building Block Methodology for instream flow assessments, and supporting research on the effects of different magnitude flows on riverine ecosystems. *Water Research Commission Report No*. 576/1/98. 452 pp.

ACKNOWLEDGEMENTS

The authors of this manual are among those who took the lead in development of the BBM and its establishment as a tool for water resource management in South Africa. Other major contributors to this process include Charel Bruwer (then of DWAF), Roy Wadeson and Greg Huggins (Institute for Water Research Environmental), Evan Dollar and Gillian McGregor (Geography Department, Rhodes University), Cate Brown and Helen Dallas (Southern Waters Ecological Research and Consulting), and Geordie Ractliffe (Freshwater Research Unit (FRU), University of Cape Town (UCT)). Kobus Erasmus and Kelvin Legge, as successive heads of Environmental Studies, DWAF, initiated and continued support for river scientists to develop skills in environmental flow assessments. Many other South African scientists, engineers and water managers took part in BBM workshops, and their contributions are gratefully acknowledged.

Major funders of the development of the BBM have been DWAF, through its funding of the BBM Workshops linked to all current major water-resource developments within the country and through the contributions of their specialists, and the WRC, through its funding of the first two editors of this manual and many of the other specialists actively involved in the field.

Karl Reinecke and Carryn Manicom (FRU, UCT) provided assistance in the final stages of preparation of this manual, for which they are gratefully acknowledged. Roy Wadeson kindly contributed two figures for the text.

The WRC, and Steve Mitchell in particular, are thanked sincerely for supporting this manual through to completion and for its publication as a WRC Technology Transfer Report.

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LIST OF ACRONYMS

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AAF	Average Annual Flow
ABF	Average Baseflow Method
AEV	Acute Effects Value
BBM	Building Block Methodology
BOD	Biological Oxygen Demand
BS	British Standards
BWE	Bulk Water Estimate
CASIMIR	Computer Aided Simulation Model for Instream Flow Requirements
CCWR	Computing Centre for Water Research (University of Natal, Pietermaritzburg, KwaZulu-Natal)
CD-ROM	Compact Disc Read-Only Memory
CEV	Chronic Effects Value
CSIR	Council for Scientific and Industrial Research
DEAT	Department of Environmental Affairs and Tourism
DO	Dissolved Oxygen
DRIFT	Downstream Response to Imposed Flow Transformations (known previously as Downstream Response to Intended Flow Transformations)
DS	Desired State (also known as Desired Future State: DFS)
DSS	Decision Support System
DVD	Digital Video Disc (or Digital Versatile Disc)
DWAF	South African Department of Water Affairs and Forestry
EAFR	Ecologically Acceptable Flow Regime
EC	Electrical Conductivity
EFA	Environmental Flow Assessment (also known as Instream Flow Assessment: IFA)
EFR	Environmental Flow Requirement (also known as IFR: Instream Flow Requirement or Ecological Flow Requirement: EFR)
EIA	Environmental Impact Assessment
EISC	Ecological Importance and Sensitivity Class
EMC	Ecological Management Class
EPAM	Expert Panel Assessment Method
EVHA	Evaluation of Habitat Method
FDC	Flow Duration Curve
FDCA	Flow Duration Curve Analysis
FLOWRESM	Flow Restoration Methodology
FMP	Flow Management Plan
FRU	Freshwater Research Unit (University of Cape Town, Cape Town, Western Cape)
GIS	Geographical Information System
GPS	Global Positioning System
HEP	Habitat Evaluation Procedure

HIS	Water quality database of the South African Department of Water Affairs and Forestry
HSI	Habitat Suitability Index (as in HIS criteria or curve)
IBI	Index of Biological Integrity
IEM	Integrated Environmental Management
IFA	Instream Flow Assessment (also known as Environmental Flow Assessment: EFA)
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirement (also known as Environmental/Ecological Flow Requirement: EFR)
IHA	Indicator(s) of Hydrologic Alteration
IHAS	Integrated Habitat Assessment System (Version 2)
IQQM	Integrated Quantity Quality Model
IWQS	Institute for Water Quality Studies (DWAF, Gauteng)
IWR	Institute for Water Research (Rhodes University, Grahamstown, Eastern Cape)
IWRE	Institute for Water Research Environmental (consulting arm of IWR, Pretoria, Pietermaritzburg and Rhodes University, Grahamstown)
MAR	Mean Annual Runoff
MCM	Million Cubic Metres (x 10^6 m^3)
MTA	Multiple Transect Analysis
NGDB	National Groundwater Database
PES	Present Ecological State
PHABSIM	Physical Habitat Simulation Model
PRA	Participatory Rural Appraisal
QAM	Mean Monthly Daily Discharge
RCC	River Continuum Concept
RCHARC	Riverine Community Habitat Assessment and Restoration Concept
RHABSIM	Riverine Habitat Simulation Program
RHYHABSIM	River Hydraulics and Habitat Simulation Program
RIVPACS	River Invertebrate Prediction and Classification System
RQOs	Resource Quality Objectives
RSS	River System Simulator
RVA	Range of Variability Approach
S.A.	South Africa
SASS	South African Scoring System (SASS4 - Version 4 of the SASS methodology)
SI	Suitability Index (as in SI curve, also known as HSI curve)
SPAM	Scientific Panel Assessment Method
SRP	Soluble Reactive Phosphate
TAL	Total Alkalinity
TAP	Technical Advisory Panel
TDS	Total Dissolved Solids
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TPC	Threshold of Potential Concern
TSS	Total Suspended Solids
TWQR	Target Water Quality Range
UCT	University of Cape Town (Cape Town, Western Cape)
U.N.	United Nations

U.S.	United States
U.S.A.	United States of America
USGS	U.S. Geological Survey (U.S. Department of the Interior)
WAMP	Water Allocation and Management Planning
WRC	Water Research Commission (Pretoria, Gauteng)
WRYM	Water Resources Yield Model
WR90	Surface Water Resources of South Africa 1990
WUA	Weighted Usable Area

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1. INTRODUCTION

Jackie King

Manipulation of the flow regimes of rivers, to provide water when and where people need it, has resulted in a growing deterioration in the condition (health) of riverine ecosystems. The science of environmental, or instream, flow assessments (EFAs or IFAs) has evolved over the last five decades, as a means to help contain, and perhaps to some extent reverse, this degradation. Most major manipulations of flow regimes are linked to in-channel large dams. Designed to store water, mainly during the wet season, and deliver it either downstream or offstream as required, dams have the potential to extensively modify natural patterns of river flow. In extreme cases, river flow can be changed from perennial to seasonal, or *vice versa*, small and medium-sized floods can be completely harnessed by the dam, and seasonal reversal of downstream flow regimes can occur as stored flood water is released during the dry season.

The costs to a country of the resulting deterioration in downstream river condition are usually externalised in water-resource developments, but are undoubtedly high and increasing. Such costs could include loss of fisheries; loss of land through bank collapse and consequent reduction in the life-span of in-channel dams; increasing levels of water pollution and linked health problems; loss of rare species, river features and habitats; proliferation of pest species; loss of the recreational and spiritual values of water systems; and loss of river resources for riparian peoples reliant on them for subsistence.

An EFA produces a description of a modified flow regime for a regulated river, designed to aid maintenance of valued features of the riverine ecosystem. The assessment is river-specific, as each catchment has its own hydrological character, and each river may have a different blend of valued features that it is wished to protect.

South Africa formally addressed the topic of environmental flows for river maintenance in the 1980s, and during the early 1990s developed its first approach for flow assessments. Named the Building Block Methodology (BBM), it was one of the world's first holistic approaches (*sensu* Tharme 1996), developed by the national community of river scientists in water-resource developments, with funding and support from the national Department of Water Affairs and Forestry (DWAF) and the Water Research Commission (WRC). The background to this development is recorded in King & Tharme (1994) and Tharme & King (1998), as is the general character of the BBM and many of the operational details of the BBM process.

This manual expands on and complements these earlier publications. It outlines coordination of the activities that comprise the BBM process, and also provides detailed chapters on the activities associated with each of the different disciplines involved. The specialists have not provided full details of how they complete their tasks, as these will be apparent to others in their fields. They have, however, endeavoured to explain **why** they perform the various tasks, so that specialists from other disciplines can appreciate the significance of all the activities.

The BBM is a methodology – a body of methods that together produces an output greater and more all-encompassing than the methods could produce individually. We view it as a tool for organising, and using in a holistic, structured way, a disparate array of knowledge and data. Each specialist chooses the methods most appropriate for his/her discipline, to produce data in the required form and nature for use in the BBM. The BBM process is used both to **guide** on this required form, and to **organise** the incoming data and knowledge to provide the required output. The output, or product, of applying the BBM is a modified flow regime, quantified in space and time. This is specific for the river, and for the desired future condition for that river. The assessment can be done for **mitigation** purposes, to advise on releases that would reduce the impacts of a proposed development, or for the purposes of **restoration**, to advise on flows that would partially reverse past degradation. Thus it can be used to help guide decisions on the management of extant or possible future water-resource developments.

The BBM is still evolving as a methodology. This manual represents a point in its development, and not the end. Future development will be closely linked to enactment of South Africa's new Water Law, which prioritises sustainable and equitable use of water resources. The BBM has already led to development of a new scenario-based environmental flow methodology, the Downstream Response to Imposed Flow Transformations (DRIFT; Brown & King 1999). This has comprehensive and structured links to the social and economic implications of changing river resources for riparian peoples depending on the river for subsistence.

In this manual, Chapters 2-7, and 20-22, provide background information on the BBM and details of how the process is managed. Chapters 8-19 outline the involvement of the most commonly used disciplines in applications of the BBM. As the BBM is a tool for organising data and knowledge, however, other disciplines could be involved as appropriate. Additional specialists that are included from time to time are those dealing with herpetofauna, water birds, or aquatic mammals.

2. ENVIRONMENTAL FLOW ASSESSMENTS: BACKGROUND AND ASSUMPTIONS

Jay O'Keeffe

2.1 THE NEED FOR ENVIRONMENTAL FLOW ASSESSMENTS

Concern over worldwide deterioration in the health of rivers has historically centred mainly on problems of water quality. In the last two to three decades, however, it has become increasingly obvious that a major factor causing their deterioration relates to the quantity of water in the rivers. With increasing demands for water from a burgeoning human population, rivers' flow regimes are being manipulated in many ways, but with two main trends. River flow is either reduced, because water is being abstracted or stored in an upstream reservoir, or it is increased, because stored water or water from another river is being released down the channel. Both may happen in the same river at different times of the year, resulting in a general tendency towards a reversal of flow patterns. Thus, in impacted rivers low flows may occur during the wet season, because water is being stored upstream, while high flows may occur during the dry season, because the stored water is released downstream to meet demand.

The flow regime is one of the overriding determinants of the character of a river ecosystem, reflecting its geographic location and the geological and topographic features of the area (Statzner & Higler 1986; Eekhout *et al*., 1997). Ecosystem components such as channel type and patterns, water chemistry and temperature, and the biotas of channel, bank and associated wetlands, reflect the nature of the river's flow pattern. In rivers where this flow pattern has been altered by man, all of these components are likely to change from their historical condition, with the degree to which this happens reflecting the severity of the flow manipulation. Were the manipulations to halt, then, to the extent that the manmade changes would allow, all of these components would tend to revert toward their natural historical condition. Artificial maintenance of the unnatural condition may bear high direct costs, such as changes in the character of the plant and animal communities, or loss of rare species. There would undoubtedly be many hidden costs also, and these are usually externalised and unquantified in water-resource developments. Such hidden costs can include bank erosion and loss of riparian land, and reduced lifespans of in-channel dams.

Wide acceptance now exists in South Africa for ensuring the sustainable use of rivers (South African National Water Act No. 36 of 1998; see Chapter 4). Environmental flow assessments reflect a new and growing science, which is centred on assessing the amount of water needed for such sustainable use. Flow assessments can be made for a river where development is planned or, equally, for an impacted one where an improvement in river 'health' (i.e. condition) is desired. The process is not simply a scientific one, but in its entirety should encompass input from all stakeholders on the condition at which the river should be maintained. The final condition decided upon may differ from river to river, according to other priorities within the catchment (see Chapter 4), and may be expressed in non-scientific terms which need converting to scientifically measurable goals (Rogers & Bestbier 1997).

2.2 UNDERLYING ASSUMPTIONS

Although a considerable body of literature exists on environmental flow methodologies, surprisingly little exists on the philosophy underpinning these. Nevertheless, questions abound among those involved in such flow assessments, from the seemingly simple "Is there **spare** water in a river?" to obviously complex ones regarding the importance of variability and predictability of flow and of ecosystem characteristics such as resilience and resistance.

The purpose of this chapter is to make explicit the assumptions that underlie most environmental flow methodologies, and specifically the BBM. The chapter does not offer unequivocal evidence to prove that these assumptions are right (there is still too much uncertainty in ecology for that), but it does offer a weight of evidence which has led to the adoption of the philosophy from which the BBM is derived. This chapter should allow the reader the opportunity to understand, and if necessary to criticise, the background thinking to the BBM. In particular, five major assumptions that are prevalent in riverine ecology, and are fundamental to the credibility of the BBM, are analysed.

- There is spare water in rivers.
- Rivers will recover from most perturbations.
- The natural disturbance regime of rivers is important for the maintenance of their biodiversity.
- The maintenance of habitat will ensure the persistence of species.
- Riverine communities, particularly those of semi-arid regions, are driven by abiotic rather than biotic processes.

On a broader scale than these questions, the validity of what is perhaps the major paradigm of conservation ecology is accepted. This is that the maintenance of natural biodiversity is the key to the health of ecosystems and to their sustainable utilisation. This was the major emphasis of Agenda 21 at the 1991 environmental summit meeting in Rio de Janeiro (United Nations (UN) 1992). In this regard, the definition of biodiversity proposed by Noss (1990) is accepted. This recognises components, structures, and functions of ecosystems at the scales of landscape, community, population and genes.

2.2.1 There is spare water in rivers

This basic assumption underlies all methods for the assessment of environmental water requirements for rivers. It is reflected in an oft-expressed wish to abstract water from a river whilst retaining its present condition. However, if the water resources of a river are to be exploited, then there will by definition be less water left in the river and this will, to a greater or lesser extent, affect the character of the riverine ecosystem.

In the U.S.A., Richter *et al.* (1997) developed a hydrology-based method for setting "streamflow-based river ecosystem management targets" which they called the "Range of Variability Approach" (RVA). In their explanation of the method, they unwittingly demonstrated the confusion of whether or not there is spare water in rivers. They suggested a "natural flow paradigm" which states: "The full range of inter- and intra-annual variations of hydrological regimes, and associated characteristics of timing, duration, frequency and rate of change, are critical in sustaining the full native biodiversity and integrity of aquatic ecosystems". Such a paradigm suggests that there is no spare water in rivers, since all the components of the flow regime are necessary to maintain natural conditions. Despite this, Richter *et al.* (1997) reported on a method which described how to reduce flows whilst maintaining natural conditions in the river, thus reflecting an assumption of 'spare water'.

Although in the strictest theoretical sense, one cannot reduce a resource without an effect on its environment, there are three main practical justifications for assuming spare water in rivers.

The naturally highly variable flow regimes of most rivers

Particularly in rivers in the more arid parts of the world, such as South Africa, annual discharge may vary by orders of magnitude from year to year. By implication, any species which persists in such a river must be able to survive, though not necessarily breed, during years when there is much less water than average. The presence of sequences of wet and dry years in South Africa, suggested by Preston-Whyte & Tyson (1988), supports the suggestion that the biota can survive repeated years when the total annual discharge is less than the average. It is not suggested that the biota will remain unchanged in permanent drought conditions. Weeks *et al.* (1996) showed that major community shifts occur among the fish fauna of the Sabie River in eastern South Africa during droughts, and also during normal low flow seasons. However, providing conditions do not drastically differ from those that have occurred in the past, recovery reflects, in the short to medium term, a dynamic flux around some common condition. It thus seems possible, over the time scales for which we have evidence, that a lower than normal flow regime which still incorporates all the major features of the natural regime would not permanently change the biota of a South African river. It is therefore suggested that, other things such as catchment condition being equal, a carefully designed modified flow regime which maintains the ecologically important components of the natural flow regime should be adequate to maintain a river's natural biota. This would allow an element of 'having one's cake and eating it', by harvesting a proportion of the river's water whilst maintaining it in a near-natural condition. However, the method of harvesting the water would be of major importance in achieving such an aim.

All rivers do not necessarily need to be maintained in a near pristine condition

Richter *et al.*'s (1997) paradigm is applied to rivers in which "the conservation of native aquatic biodiversity and protection of natural ecosystem functions are primary river management objectives". One of the most powerful innovations of the South African approach has been to attempt to define specific management objectives for each river, and often for different stretches of a river. This approach, incorporating a management goal known originally as the Desired State (DS) and more recently as the desired Ecological Management Class (EMC), reflects the national reality that most if not all the country's rivers are modified from a pristine condition. An achievable EMC is thus set for each river, related to its present status and importance (Chapter 4). For example, the Letaba River, which flows through the Kruger National Park, is already degraded upstream of the Park, largely due to over-abstraction of water and associated polluting effects (Chutter & Heath 1993). The river is recognised as very important at a regional and national level, and its EMC, amongst other aims, sets the restoration of perennial flow as a major objective. The upper reaches of the Great Kei River in the Eastern Cape, on the other hand, once had ephemeral flow (DWAF 1994a). For more than 20 years, however, the flow has been modified to an elevated continuous flow providing for downstream irrigation from the Waterdown Dam. The river is presently degraded from its natural condition, and the EMC for its upper reaches reflects the aim to maintain these present conditions, rather than to attempt to rehabilitate the river to some uncertain natural condition. The recognition that most rivers are no longer pristine, and the setting of achievable conservation goals tailored to specific rivers, allows a river-by-river assessment of the amount of water that can be abstracted without compromising the chosen EMC.

Major floods cause structural damage to rivers, and carry water that can be intercepted by dams and used to augment low flows

This is especially true for rivers flowing through developed catchments (Kochel 1988), where natural vegetation has been removed and riparian buffer strips compromised. The definition of damage in this section might be controversial, since many ecologists would view the erosion and bed movement caused by major floods as a resetting mechanism, periodically necessary for maintenance of the channel and its physical heterogeneity. Whilst this may be true for small to medium floods, with a return period of less than 1:5 years, larger floods do progressively more structural damage, from which habitats and biota take longer to recover. In over-exploited catchments, it is often the very large floods that complete the degradation begun by anthropogenic activities such as vegetation removal and overgrazing. An obvious, although unquantified example, is the Mfolozi River in KwaZulu-Natal, the lower reaches of which were devastated by cyclone Demoina in 1984 (Allanson *et al.,* 1990). The riparian zone was extensively eroded, and the channel heavily silted. These structural changes are not likely to be reversed within less than century time scales.

There are thus possible reasons for accepting that, if water abstraction from rivers can be carefully managed, the effects on the river's biota can be minimised, or at least contained to a pre-agreed level. Uncertainty remains, however, about the effects of flow reduction on geomorphic processes in rivers, and this is an area in which Richter *et al.*'s (1997) paradigm may be valid. For instance, many geomorphologists feel that all flows 'work' the riverbed to a greater or lesser extent, thus contributing to maintenance of the physical condition of the channel bed and banks. In contrast, Davies *et al.* (1994) suggested that the transport of sediment in arid zone systems is dominated by events of low frequency and high magnitude. There does not appear to be general agreement on this. Kochel (1988) reviewed the ongoing debate about the effects of "infrequent, large-magnitude floods, versus the cumulative effect of frequent, small-magnitude floods, on stream channels and floodplains". He suggested that there could be no general conclusions, as the effects of individual floods depend on a suite of interdependent variables, including climate, channel and basin characteristics.

As a result of this uncertainty, there is a real difficulty attached to predicting the effects of reduced flows on the sediment processes which are crucial to maintenance of channel morphology and therefore also of habitat diversity. Impoundments can be managed to augment low flows, and in most dammed rivers very large floods are not seriously attenuated. So it is usually the small to medium floods that are intercepted, and the result may be either an increase in sediment deposition, causing progressive bed siltation, or an increase in scouring, depending on the sediment sources downstream of the flow regulating structure.

2.2.2 Rivers will recover from most perturbations

Rivers appear to recover rapidly from small-scale, short-term disturbances. Townsend (1989) commented on the speed with which invertebrates are able to recolonise disturbed patches of riverbed, and Townsend & Hildrew (1994) concluded that stream invertebrate communities are resistant (persist unchanged) to very small scale disturbances, and resilient (recover to pre-disturbance condition) to larger scale ones. Townsend (1989) emphasised the importance of refugia in recolonisation. For aquatic invertebrates, the obvious refugia are undisturbed upstream reaches or tributaries, other similar rivers for those insects with aerial adults, and the hyporheos (e.g. Stanford & Ward 1988). Fish are more mobile (within river systems) but less able to hide in the hyporheos, and (mostly) unable to leave the water, but they can utilise floodplains, backwaters, residual pools, and tributaries as refugia.

Weeks *et al.* (1996) documented the extraordinary persistence of fish communities at different scales in the Sabie River during an extreme drought in 1991/92. Fourteen species of fish persisted for three months in a small (ultimately 5 m by 2 m) isolated pool in the Sand tributary. At a larger scale, gold-mining seepage reduced the mainstream Sabie River to a "sterile stream" in the early years of the century, according to the then warden of the Kruger National Park, Col. Stevenson-Hamilton (quoted in Pienaar 1985). A survey of the benthos in 1933 revealed nothing alive in the river (Pienaar 1985). Mining next to the river ceased in the 1940s and the river recovered to become biologically one of the most diverse in South Africa (O'Keeffe *et al.*, 1996). This was presumably a result of recolonisation from non-mined tributaries. However, Weeks *et al.* (1996) found that some of the less mobile fish species were still absent from the upper middle reaches of the river adjacent to the mined areas, presumably because cascades and waterfalls inhibited migration. The three year study of the Sabie River by Weeks *et al.* (1996) also demonstrated the resilience of the biota to droughts and floods, showing that all the fish species found in the river during earlier surveys (Pienaar 1978) were still present, despite some extreme low and high flow events.

Studies in other parts of the world have shown a similar large-scale recovery of aquatic ecosystems, notably in Lake Washington in Seattle and the River Thames (Moss 1988). There is thus, no doubt that riverine systems can recover remarkably well if the source of disturbance (in these cases pollution) is withdrawn.

That rivers are not resilient in the face of sustained perturbations, however, has been shown by many studies. In South Africa, two contrasting examples illustrate this point. Increasing urban development along the Buffalo River (O'Keeffe *et al.,* 1990), particularly upstream of the main supply reservoirs, has led to chronic pollution of the river. Regulated flow from an interbasin transfer in the Great Fish River (O'Keeffe & De Moor 1988) has led to dominance of the aquatic invertebrate community by stock-biting blackfly, *Simulium chutteri*. Hildrew & Giller (1994) concluded that: "stream communities track average environmental conditions faithfully and are fragile in the face of ... sustained perturbations".

Although they may be robust in the face of short-term disturbances to the biota, riverine ecosystems are much less resilient to structural damage. Such damage may be caused when large floods pass down rivers in over-developed catchments, particularly when the riparian zone has been denuded of natural vegetation. Damage to the Mfolozi River by cyclone Demoina has already been mentioned (Section 2.2.1). Kochel (1988) provided a table of the geomorphological effects of more than 25 floods in different parts of the U.S.A. Effects ranged from bank erosion and channel widening or deposition, to floodplain erosion or deposition. He also documented some large floods that caused very little structural change. He concluded that the types of rivers that are vulnerable to flood damage are those which are characterised by flashy hydrographs; high channel gradients; abundant coarse bedload; low bank cohesion; and channel shapes in which floods cause high velocity flows. These characteristics are most common in semi-arid and arid regions, where intense, short duration, local rainfall is common (Kochel 1988).

Niemi *et al.* (1990) reviewed more than 150 case studies in which some aspect of resilience in freshwater systems was reported. Most involved disturbances caused by pollution, but eight were cases involving flood disturbance. They concluded that: "all systems ... seem to be resilient to most disturbances, with most recovery times being less than three years. Exceptions included when (1) the disturbance resulted in physical alteration of the existing habitat, (2) residual pollutants remained in the system, or (3) the system was isolated and recolonisation was suppressed".

The assumption that rivers recover from most perturbations appears to be justified, as long as the perturbation is not severe or persistent. Important exceptions to this rule, however, occur with permanent and severe flow modification, when there is physical damage to the river channel, riparian zone or floodplain, or where there are no or degraded refugia from whence recolonisation can occur. Rivers that have recovered from past severe disturbances may not be able to do so again. For example, the Sabie River may have recovered from the mining pollution of the first half of the century (see above), but it can no longer be assumed that such resilience is still inherent in the system. Many of its tributaries, formerly refugia, now have catchments disturbed by forestry plantations, irrigated crops, overpopulation and overgrazing. As anthropogenic disturbances of catchments increase, the ability of the rivers to recover from impacts relentlessly decreases.

2.2.3 The natural disturbance regime of rivers is important for the maintenance of their biodiversity

An ecological concept to which much discussion has been devoted is that of disturbance and patch dynamics. Early contributions were bedevilled by different definitions of ecological disturbance (e.g. only disruptions larger than those normally experienced in an organism's lifetime should be classed as ecological disturbances). Now there appears to be a generally accepted definition of disturbance, which was well articulated by Townsend (1989): “any relatively discrete event in time that removes organisms and opens up space or other resources”. This confines disturbances in the sense of the concept to short-term events, and incorporates both natural disturbance regimes and anthropogenic disturbance (*sensu* Poff & Ward 1990).

The assumption that the maintenance of the natural amplitude of disturbance is important derives from the idea that different flows are responsible for creating heterogeneous habitat conditions in time and space (stream patchiness) (Townsend 1989). These habitat conditions in turn provide for a diversity of niches and refugia under all conditions (Townsend 1989). Hildrew & Giller (1994) pointed out that the existence of a variety of channel forms, floodplains and marginal habitats makes the likelihood of catastrophic mortality through the whole system at the same time extremely unlikely. They saw maintenance of such a diversity of habitats as akin to “spreading the risk” at the community and population level. They also reviewed evidence to confirm this view, illustrating that, even during peak discharge events, there are areas within rivers that have low velocities and shear stresses.

Investigations of disturbance in rivers have generally concentrated on the effects of floods, but the consequences of abnormally low flows, or the cessation of flows, are equally important. In South Africa, the constant elevation of low flows by dam releases in the Vaal, Orange and Great Fish rivers has led to the dominance of the invertebrate fauna by *S. chutteri* (O’Keeffe & De Moor 1988; see above). O’Keeffe & De Moor (1988) and Palmer & O’Keeffe (1990) compared the invertebrate communities of the Great Fish River before and after regulation. They showed that there were roughly the same number of invertebrate taxa in the river during these stages, but that only 30% of the taxa were common to both stages. *Simulium chutteri*, which was rare before regulation, constituted at least 95% by number of the invertebrate community after regulation.

Poff & Ward (1990) concluded that a consensus has emerged on the significance of disturbance in shaping ecological processes and patterns in rivers. They stated that: “The long-term regime of natural environmental heterogeneity and disturbance may be considered to constitute a physical habitat template which constrains the types of species attributes appropriate for local persistence”. In an earlier review of the significance of disturbance in stream ecology, Resh *et al.* (1988) concluded: “Disturbance is an important topic in stream ecology. It can be responsible for a host of temporal variations in spatial patterns. The frequency, intensity, or severity of disturbance will determine when, if ever, a community will reach equilibrium. Disturbance will have a major impact on productivity, nutrient cycling and spiralling, and decomposition. In fact, to some of us, disturbance is not only the most important feature of streams to be studied, it is the dominant organising factor in stream ecology.”

Although the above examples may be sufficient to justify the assumption that natural disturbance is important, there is still much debate about the details of disturbance theory. For example, Poff (1992) disputed Resh *et al.*’s (1988) contention that disturbances are by definition unpredictable, suggesting (amongst other things) that physically-based disturbances should be defined in relation to specific ecological responses, which may or may not be predictable. The problem for EFAs is to evaluate how much of the natural disturbance regime can be sacrificed without significantly affecting the future state of a river and, similarly, how much anthropogenic disturbance the riverine biota can tolerate or recover from.

2.2.4 Maintenance of habitat will ensure the persistence of species

Southwood (1978) coined the phrase "habitat template", on which the life histories of organisms were seen as being moulded by natural selection. He advised that an understanding of habitat provides an appropriate beginning for ecological studies. For most environmental flow studies in South Africa, a cursory study of habitats is the beginning, and often the end, of an understanding of organisms' requirements. Even on this topic, insufficient time and funds are allocated to develop a true understanding of the habitat requirements of all, or even selected key, species. Instead, as an interim measure while knowledge develops, the target has had to be the maintenance of physical, specifically hydraulic, habitat, on the assumption that this will sustain the biota (King & Tharme 1994).

In discussing the development and application of environmental flow methodologies, and particularly the Instream Flow Incremental Methodology (IFIM; Chapter 3), Orth (1987) concluded that the availability of physical habitat is not the only factor limiting fish populations, and therefore indices of microhabitat availability are not expected to be consistent predictors of fish population density. Gore & Nestler (1988) agreed with this view, but pointed out that the primary purpose of IFIM is prediction of changes in available habitat with flow changes rather than simulation of ecological interactions. They also offered the opinion that the additional predictive power gained from including biological interactions in a methodology such as IFIM would be very costly, and such additions are not needed in the context of most environmental flow studies. This may be so, but a sound knowledge of the use of different habitats by the biota is a prerequisite for judging the effects of flow-related habitat reduction.

Certainly, successful completion of life cycles of riverine species is dependent on more than the availability of hydraulic habitat. Moreover, even the description of habitat needs to take into account the different requirements of each species, their sequential life history stages, and the need to maintain the habitats of their food species. Many environmental flow methodologies acknowledge the importance of other physical and chemical controls such as temperature and water chemistry, but often treat these as at least partially linked to catchment position and management, and thus outside the province of flow manipulation alone. A comprehensive effort to maintain the ecological health of a river will obviously require a catchment management plan as well as a flow management plan.

Although it is clear that even providing ideal flows will not maintain the natural communities in a polluted river, that does not preclude the necessity to reserve specified flows for the river. By doing so, options for enhancing the river's health will still be open should sources of pollution be removed.

The case for including biological interactions in environmental flow studies is discussed under the following section.

2.2.5 Riverine communities, particularly those of semi-arid regions, are driven by abiotic rather than biotic processes

Environmental flow methodologies are mainly concerned with one component of the river ecosystem - its flow regime - thereby reflecting the regime's overwhelming importance in sculpting of the ecosystem. However, how extensive is the significance of other abiotic forces and of biotic interactions in determining the nature of the ecosystem? Hildrew & Giller (1994) reviewed the evidence, and concluded that it was largely true, albeit somewhat simplistic, that abiotic processes are the main determinants of river communities. They stated: “Stream ecologists have assumed that temporal variations in lotic communities are purely the result of physicochemical disturbances ... This probably is overwhelmingly the case, although we ought to be aware that deterministic, biotic interactions can produce highly unstable or even chaotic outcomes”. They cite the effects of disease and introduced species as instigators of instability in rivers. These are relevant examples, but do not affect the validity of the assumption for flow assessment purposes that the flow regime is an overriding factor governing the nature and stability of communities in a river. For example, introduced carp have been highly successful colonisers of regulated sections of rivers such as the Vaal in South Africa, but flow regulation has undoubtedly created the conditions for their success.

At smaller scales, flow governs the hydraulic conditions that have been shown to mediate biotic interactions. Hildrew and Giller (1994) quote the example of differing velocity preferences between a predatory triclad and larval blackfly, which affect their encounter rate and the predator’s prey handling abilities.

Statzner has long been a proponent of the view that the distribution of lotic organisms can largely be explained in terms of their preferences for particular hydraulic conditions (Statzner *et al.*, 1988). More recently Statzner & Borchardt (1994) concluded that shear stress explained “far more than 50% of the variability” in the ecological responses of a baetid mayfly and its plecopteran predator. They pointed out, however, that biotic factors were also important. Where the predatory species achieved dense populations, it could modify the patchy distribution of its prey, compared to what would be expected from flow preferences alone. Their general conclusion, despite criticism from Petersen & Sangfors (1991), remained the same as that of Statzner & Higler (1986), that: “stream hydraulics are the most important factor governing the zonation of lotic benthos”.

There are obviously abiotic factors other than flow that can, when changed, become the dominant impactor on riverine biota. These factors include water chemistry variables, temperature, and sediment load. At present, it is usually impossible to predict in adequate detail how these will change with changing flow, or how the changes will affect the riverine biota. For example, flow reduction will inevitably affect water quality, especially if there are sources of poor quality water coming in downstream of water abstraction points. Obviously, it is an unwise use of a scarce resource to recommend increased flows to improve water quality, and the better answer is to address the sources of pollution. The use of environmental flow methodologies requires an understanding of the different factors affecting the biota, and the reasons for their effects. This, however, does not invalidate the hypothesis that a carefully designed modified flow regime should be able to maintain the biota at some preconceived condition, provided other influencing factors are also addressed.

2.3 CONCLUSIONS

Fisher (1997) pointed out that river research has contributed only modestly to general ecological theory, and that river ecology is a “habitat-defined” rather than a “theory-defined” subdiscipline of ecology. This is particularly true of applied river ecology as typified by the assessment of environmental flow requirements

(EFRs). The essential distinction between applied and basic ecological research was articulated by Poff (1997): "A fundamental goal of basic ecological research is to **understand** how observed ecological patterns are generated by specific processes or constraints, thus allowing for valid generalisations. Applied ecological research, by contrast, generally seeks to **predict** ecological patterns, often for the purposes of resource management".

Environmental flow methodologies sit firmly within the latter camp, where understanding causes is less important than the ability to make accurate predictions. However, as Poff (1997) also pointed out, an understanding of processes and mechanisms considerably strengthens the use of purely correlative relationships, and may make predictions more robust and generally applicable. Although river ecologists may not be contributing (or aiming to contribute) to fundamental ecological theory, it is therefore important for them to check their assumptions against general theory, and use the evidence for such theories to understand the strengths and limitations of the methods applied.

In this chapter it is suggested that most of the assumptions inherent in environmental flow methodologies used in South Africa are justified, at least for coarse grain medium-term (ten years) predictions of biotic change in rivers as a result of flow modifications. It is less certain, however, whether or not channel processes are as robust to flow modifications. Physical habitats are arguably the vital link between hydrology and the distribution and abundance of organisms in rivers. In setting EFRs, it is therefore essential to know how much work (*sensu* Brookes 1994) is being done on the riverbed by flows of different magnitudes. Recent research by Van Niekerk & Heritage (1994) resulted in a model of sediment processes for the lower Sabie River, which was incorporated into a rule-based model (Jewitt *et al.*, 1998) to predict changes to fish communities. This model reflects the long-term effects of changing physical habitat, through the following sequence of abiotic and biotic reactions:

Modification of flow regime
⇩
Changes in sediment processes
⇩
Long-term changes in habitat types and abundance
⇩
Permanent changes in fish communities

Initial results from this model are encouraging, but predictions need to be verified, and there is no clarity as to how far the results are generally applicable to other rivers. There is no doubt that a major research priority for EFAs is to clarify the relative importance of flows of different magnitude in structuring river channels, at scales from microhabitat patches to whole river reaches.

One of the saving graces of environmental flow methodologies is that the results do not usually have to be too precise, because they aim for predictions at large scales (trading off grain for perspective (Hildrew & Giller 1994), and because management capabilities for rivers are similarly imprecise. This is not to deny that small disturbances within ecosystems can sometimes have spectacular consequences, but simply to acknowledge that such potential effects are outside the scope of present predictive models and management practice for rivers. Another saving grace for the application of EFAs in semi-arid environments such as South Africa is that the river organisms live in highly variable and unpredictable flow regimes (Davies *et al*., 1994). Such organisms are more likely to spend their lives surviving floods and droughts than creating complex interacting communities that are mediated by competition. "Hardy opportunists" is the phrase most often applied to species that survive the rigours of South African rivers (Harrison 1978; O'Keeffe 1986; Davies *et al*., 1994), confirming the assertion of Reice *et al.* (1990) that "many stream communities are in a state of perpetual recovery from frequent disturbances". This perspective led Hildrew & Giller (1994) to suggest a "clinging to the wreckage" model of community organisation, in which species are either entirely non-interactive or the recurrence time of disturbances is too short to allow interactions to eliminate species (Huston 1979, cited in Hildrew & Giller 1994). Among such disparate collections of organisms, it is also less likely that small changes will result in major ecosystem consequences.

Acknowledging the robustness of semi-arid river ecosystems does not equate to accepting that their functioning is easier to understand or to manage than those in more temperate climes. Living organisms encompass levels of adaptation and fragility, presumably as a result of millions of years of submission to the capricious forces of evolution, that are unlikely to be captured at any high level of resolution by today's simplistic ecosystem models. In addition, the cumulative uncertainties of predicting the behaviour and consequences of processes that influence communities (e.g. the hydrological cycle, sediment dynamics, nutrient cycling), result in ecosystem modelling being an imprecise enterprise. The fuzzy logic inherent in rule-based models of the type used by Jewitt *et al.* (1998) to predict the effects of flow modification on the communities of the Sabie River then comes into its own. Such models (the BBM essentially represents one) are able to accommodate the scientist's expertise (often wrongly conceived to be intuition) that is intractable in mathematical models.

The major contributions that developments in South African EFAs have made, have been the use of available ecological theory to produce achievable methods for setting environmental flows for rivers. Specifically, the South African contributions have been:

- to develop methodologies which produce credible flow recommendations within suitable time frames. (i.e. geared to the phases of planning and construction in water-resource development projects);
- to develop an inclusive process, which progresses by consensus rather than conflict, and involves scientists from different disciplines, planners, managers, engineers, and decision makers at each step;
- the setting of achievable environmental objectives for rivers, through a process of linking specific modified flow regimes with different levels of river health;
- making flow recommendations that reflect and are synchronised with, the natural variability of rivers;
- recognising the importance of low (or even no) flows as contributing to the maintenance of the natural community structure of riverine ecosystems.

3. AN OVERVIEW OF ENVIRONMENTAL FLOW METHODOLOGIES, WITH PARTICULAR REFERENCE TO SOUTH AFRICA

Rebecca Tharme

3.1 INTRODUCTION

In an international context, the development and application of methodologies for prescribing EFRs (also known as instream flow requirements (IFRs), began as early as the 1950s, in the western U.S.A, with marked progress during the 1970s, primarily as a result of new environmental legislation (Stalnaker 1982; Trihey & Stalnaker 1985). Outside the U.S.A., the process by which environmental flow methodologies evolved and became established for use is less apparent, as there is little published information on the topic (Tharme 1996). In some countries, for instance England, Australia, New Zealand and South Africa, EFAs for rivers only began to gain ground as late as the 1980s. Other parts of the world, including parts of eastern Europe, and much of South America and Asia, appear less advanced in the field, with little published mainstream literature that deals specifically with environmental flows. This suggests that many countries have either not yet recognised the critical importance of EFAs in the long-term maintenance and sustainability of freshwater systems or have not made such assessments a priority (Tharme 1996).

Presently, a vast body of formal methodologies exists for prescribing environmental flow needs. These methodologies have been reviewed in depth by, *inter alia*, Stalnaker & Arnette (1976), Wesche & Rechard (1980), Morhardt (1986), Estes & Orsborn (1986), Loar *et al*. (1986), Kinhill Engineers (1988), Reiser *et al.* (1989a), Gordon *et al.* (1992), Growns & Kotlash (1994), Tharme (1996, 1997a), and Stewardson & Gippel (1997). It should be noted that the information presented in this chapter largely represents the status of methodologies as at early 1998, corresponding largely with the timeframe over which the BBM evolved. Several more recent references on the topic, notably the reviews by Dunbar *et al.* (1998), Arthington (1998a), Arthington & Zalucki (1998), Arthington *et al.* (1998a, b), and King *et al.* (1999) have been added as sources of further information or for clarity. Probably the most up to date information on the global situation with regards to EFAs is contained in Tharme (2000).

The majority of environmental flow methodologies can be grouped into four reasonably distinct categories: hydrological (Section 3.2); hydraulic rating (Section 3.3); habitat simulation (Section 3.4) and holistic (Section 3.5). There are also a number of hybrid approaches which comprise elements of one or more of these main types of methodology, case-specific techniques relying wholly on professional judgement, and several alternative approaches to dealing with environmental flow issues (see Tharme 1996, 1997a, for examples).

Many current methodologies are sufficiently robust and generalised in nature to be broadly applied, for example to different types of river or ecosystem component. This is particularly true of holistic type methodologies, which aim to address EFRs for the maintenance of the riverine ecosystem in its entirety (Section 3.5). Historically, however, and most notably with approaches developed in the U.S.A., the majority of hydraulic rating and habitat simulation methodologies (Sections 3.3 & 3.4), have been developed to address the EFRs of instream biota. They have usually targeted economically important fish species, where flows to facilitate fish spawning and passage often represent the primary environmental flow objective(s). In more recent years, there has been a gradual increase in efforts to address the EFRs for other components of the riverine ecosystem, such as benthic macroinvertebrates (Campbell 1991; King & Tharme 1994), geomorphology (Section 3.6), riparian vegetation (Section 3.7), riparian and instream wildlife (Section 3.8), and water quality (Section 3.9). This has, in many cases, necessitated a divergence from an emphasis on relationships traditionally explored in methodologies developed to address IFRs for fish, to explore other kinds of information better suited to the component under investigation.

In Section 3.10, the types of environmental flow methodology that are most commonly applied in various countries throughout the world or are recommended for future investigation are summarised. Particular emphasis is given to the current situation in South Africa in Section 3.11.

3.2 METHODOLOGIES BASED ON HYDROLOGICAL DATA

3.2.1 The nature of methodologies based on hydrological data

The simplest environmental flow methodologies rely on the use of hydrological data, usually in the form of historical flow records, for making environmental flow recommendations. They are usually referred to as fixed-percentage or standard-setting methodologies, where a fixed proportion of flow, often termed the minimum flow (Cavendish & Duncan 1986; Milhous *et al.*, 1989), represents the environmental flow recommendation intended to maintain the fishery or other highlighted ecological feature at some acceptable level. Often, hydrology-based methodologies include catchment variables or are modified to include professional judgement, and hydraulic, biological and geomorphological criteria (e.g. see Estes 1996), in addition to hydrological data (Tharme 1996).

3.2.2 The present status of methodologies based on hydrological data

There are numerous methodologies that rely primarily or solely on hydrological data for deriving environmental flow recommendations, and Tharme (1996, 1997a, 2000) and Dunbar *et al.* (1998) provide a review of several of them. Of such methodologies, the **Tennant Method** (or Montana Method) (Tennant 1976), is currently still the second-most widely used environmental flow methodology in North America (Reiser *et al.*, 1989a). The basic method (Tennant 1976), or modifications thereof (see Estes 1996, & Dunbar *et al.*, 1998, for examples), is also used routinely in many other countries, often as the primary, basinwide scoping level of a two-tier system of environmental flow assessment (Tharme 1996; Dunbar *et al.*, 1998).

Although superficially a standard-setting approach, the Tennant Method differs from most other methodologies reliant on hydrological indices in that expert opinion and considerable field hydraulic and biological data collection were involved in its development. The method addresses environmental flows for fish, wildlife, recreation and related environmental resources. Percentages of the average annual flow (AAF), where various percentages of AAF correspond to defined categories of environmental flow conditions, are used to formulate river baseflow regimes on a seasonal basis, to satisfy environmental flow needs (Tennant 1976). For example, 10% AAF represents the minimum instantaneous flow recommended to sustain short-term survival habitat for most aquatic biota. A critique of the Tennant Method is provided in Tharme (1996, 2000), and more general advantages and disadvantages of the approach are given in Section 3.2.3.

Another common hydrology-based methodology applied worldwide in its general form, is **Flow Duration Curve Analysis** (FDCA). Flow duration curves (FDCs) display the relationship between discharge and the percentage of time that it is exceeded. Where historical flow records are analysed over specific durations in FDCA (Gordon *et al.*, 1992), FDCs are used to derive specific flow percentiles (percentage exceedance values) associated with required suitable river conditions, often in combination with professional judgement, to produce environmental flow recommendations. For instance, the Q_{95} Method is based on the 95% exceedance value on a seasonal FDC (Gustard *et al.*, 1987, cited in Dunbar *et al.*, 1998). Specific strengths and weaknesses of the approach are given in Tharme (1996, 1997a).

More recent methodologies, based primarily on hydrological indices, also incorporate biological criteria in some instances. These include the September Median Flow Method (Reiser *et al.*, 1989a), Texas Method (Matthews & Bao 1991), Annual Minima Method (Cassie & Nassir 1994, cited in Dunbar *et al.*, 1998) and Basic Flow Method (Palau & Alcazar 1996). Tharme (1996, 1997a, 2000) and Dunbar *et al.* (1998) review these approaches. The **RVA** (Richter *et al.*, 1996, 1997) is one of several new methodologies that is considered to hold considerable merit for further investigation (Tharme 1997a, 2000; Dunbar *et al.*, 1998). It aims to provide a comprehensive statistical characterisation of ecologically-relevant characteristics of a flow regime. Briefly, the natural range of hydrological variation is described using 32 different hydrological indices derived from long-term daily flow records (Richter *et al.*, 1997). The indices, termed Indicators of Hydrologic Alteration (IHA; Richter *et al.*, 1996) are grouped into five categories based on the regime characteristics; magnitude, timing, duration, frequency and rate of change of discharge. Flow management targets, which can be monitored and refined over time, are set as ranges of variation of each hydrological parameter.

3.2.3 General strengths and deficiencies of methodologies based on hydrological data

Strengths

Methodologies based on flow records are typically inexpensive, rapid, desktop approaches, requiring only historical flow records. As such, they are highly appropriate at the reconnaissance level of water-resource development and for planning purposes, providing routine, simple, yet low-resolution estimates of quantities of water to be set aside for environmental maintenance. The more sophisticated methodologies, like RVA, particularly those that utilise key, ecologically-relevant hydrological indices, have the potential to be modified to produce regionalisation methods on a river ecotype basis and are also able to provide a useful monitoring function. In addition, the sets of hydrological indices derived from such methods can be incorporated as subcomponents of holistic type methodologies, as has been done in the BBM. Finally, it is likely that hydrology-based methodologies will continue to be used commonly in future as rapid assessment methods, and hence will continue to be recognised internationally, with increasing efforts to advance and develop them for application in specific situations worldwide.

Deficiencies

From an ecological perspective, this type of methodology is especially simplistic in that it does not adequately address the dynamic and variable nature of the hydrological regime. Moreover, the long-term effects of maintaining the minimum flows are rarely the same as the naturally occurring infrequent, short-term effects reflected by instantaneous events in the historic record. The methodologies are also highly limited, in the majority of applications, by the absence of ecological information as input. This restricts their flexibility, degree of resolution, and scope for use relative to other types of methodology, as well as rendering them open to considerable criticism. There is also the risk that the low resolution, single figures that most often constitute the output will be routinely applied across different countries, geographic regions and river types, without sufficient understanding of the ecological implications. Hence, professional judgement is essential when such methodologies are employed. Such disadvantages render hydrological methodologies appropriate only at a planning level, and in cases that are not high profile, where no negotiation is involved in the decision-making process. They should also be applied with extreme caution in countries or regions with hydrological regimes that differ vastly from their place of origin.

3.3 HYDRAULIC RATING METHODOLOGIES

3.3.1 The nature of methodologies based on simple hydraulic relationships

From the 1970s onwards, initially in North America, there was rapid development of incremental methodologies that utilised a quantifiable relationship between the quality of an instream resource, such as fishery habitat, and discharge, to calculate EFRs. These examined, for the first time, the effects of specific increments in discharge on instream habitat (Tharme 1996). Pioneers of this approach included Collings *et al.* (1972, cited in Trihey & Stalnaker 1985) and Waters (1976). Two groups of transect or cross-section based methodologies, founded on a habitat-discharge relationship, progressively evolved, namely hydraulic rating and habitat rating (Section 3.4) methodologies (Trihey & Stalnaker 1985).

Hydraulic rating methodologies measure changes in various single river hydraulic variables such as wetted perimeter or maximum depth, at a single cross-section. This is used as a surrogate for habitat factors that are limiting for riverine biota, to develop a relationship between habitat and discharge from which to derive environmental flow recommendations (Loar *et al.*, 1986).

Tharme (1996) and Dunbar *et al.*, (1998) consider these methodologies in many ways a ‘halfway house’ in that they generally represent the precursors of more sophisticated habitat simulation methodologies (Section 3.4). The latter approaches integrate hydraulic data, collected from multiple cross-sections, with biological data on the physical habitat requirements of the biota. However, hydraulic rating methods merit some attention in that historically, they have frequently been used in parts of the U.S.A. and are still routinely applied today (Tharme 1996).

3.3.2 Commonly applied hydraulic rating methodologies

Tharme (1996) reviews commonly applied hydraulic rating methodologies and a number of associated hydraulic simulation models used to derive EFRs. Probably the most commonly used hydraulic rating methodology worldwide, and overall the third most used methodology in North America (Reiser *et al.,* 1989a; Section 3.10), is the **Wetted Perimeter Method**. This method simply uses the relationship derived from changes in river wetted perimeter at a single cross-section, usually across a riffle (as riffles tend to be the most productive benthic habitat), with changes in discharge, as the basis for an environmental flow recommendation. Minimum or optimal flows, usually for fish spawning or maximum production by benthic invertebrates, are generally identified from a discharge near the breakpoint of the wetted perimeter-discharge curve (e.g. Collings 1974, cited in Stalnaker & Arnette 1976; Prewitt & Carlson 1980). Tharme (1996, 1997a) and Gippel & Stewardson (1996) review the method, and the latter authors document a recent application of the technique.

3.3.3 General strengths and deficiencies of hydraulic rating methodologies

Strengths

Hydraulic rating methodologies can be considered an advance over purely hydrology-based ones in that they incorporate ecologically-based information on the instream, physical habitat of the biota. They enable a fairly rapid, though simple, assessment of flows for the maintenance of such habitat areas for requirements such as invertebrate production, fish spawning and passage. They are also sufficiently flexible to be applied to many aquatic species and activities, as well as being only low to moderately resource-intensive. Furthermore, they can be used as reconnaissance methods at a regional or catchment-wide level, on all sizes and types of stream.

Deficiencies

The methodologies rely on the highly simplistic assumption that a single hydraulic variable or group of variables can adequately represent the flow requirements of a target species for a particular activity. Indeed, the EFRs of target organisms are ascertained only by inference, using hydraulic variables as surrogates. Placement of the single cross-section, and the quality of the relationships between discharge and hydraulic parameters, are critical to the results obtained. Notably, explicit links with the hydrological regime are often not considered in the assessment, and the output is seldom dynamic in spatial or temporal resolution. Outputs also tend to be of only low to moderate resolution. Finally, the focus on instream habitat for target biota means that these methodologies cannot be readily used for other out-of-channel components of the riverine ecosystem, such as riparian vegetation.

3.4 HABITAT SIMULATION METHODOLOGIES

3.4.1 The nature of habitat simulation methodologies

Habitat simulation methodologies, also referred to as habitat rating (Loar *et al.,* 1986), microhabitat or habitat modelling methodologies (Dunbar *et al.,* 1998), attempt to assess EFRs on the basis of biotic responses to flow at the level of instream habitat. Within such methodologies, changes in physical microhabitat with discharge are modelled using data on one or more hydraulic variables, most commonly depth, velocity, substratum composition, cover and, more recently, benthic shear stress (Tharme 1996). These data are collected at multiple cross-sections within the study reach. Simulated available habitat conditions are linked with information on suitable and unsuitable microhabitat conditions for the target species, lifestages, assemblages and/or activities, for instance using suitability index (SI) curves (Bovee & Zuboy 1988). The final outputs, usually in the form of habitat-discharge curves for the target biota, are used to predict optimum discharges as environmental flow recommendations.

3.4.2 Commonly applied habitat simulation methodologies

Tharme (1996) and Dunbar *et al.* (1998) provide an overview of some of the vast number of habitat rating approaches that in the past have been commonly used and, in some instances, still are used to calculate environmental flows. For example, *inter alia*: the Oregon Usable Width Method (Thompson 1974, cited in Stalnaker & Arnette 1976); U.S. Forest Service R-6 Method (Swank 1975, cited in Growns & Kotlash 1994); and various forms of the generic technique, Multiple Transect Analysis (MTA; Richardson 1986).

The Instream Flow Incremental Methodology

Of all currently available habitat simulation methodologies, IFIM is considered by many ecologists to be the most sophisticated, and scientifically and legally defensible methodology available for quantitatively assessing EFRs for rivers (Gore & Nestler 1988). It is, therefore, the most commonly used environmental flow methodology worldwide, particularly in the U.S.A. where it was developed (Mosley 1983; Reiser e*t al.*, 1989a; Gan & McMahon 1990a, b; Bullock *et al.*, 1991; Gore *et al.*, 1991; King & Tharme 1994; Jowett & Richardson 1995; *inter alia*). However, the methodology has also received an enormous amount of criticism over the years (Mathur *et al.*, 1985; Shirvell 1986; Scott & Shirvell 1987; Gan & McMahon 1990a; King & Tharme 1994). Comprehensive accounts of IFIM are given in Milhous *et al.* (1989), Gan & McMahon (1990b), King & Tharme (1994), and Tharme (1996), and a brief description of it is given below. Tharme (1996, 2000) provides a summary of specific criticisms levelled at IFIM, while some of its general strengths and weaknesses, and those of similar habitat simulation approaches, are given below (Section 3.4.3).

Essentially, IFIM comprises a set of analytical procedures and computer models, including its main component, the **Physical Habitat Simulation Model**, PHABSIM (Milhous *et al.*, 1989; Nestler *et al.*, 1989; Stalnaker *et al.*, 1994). In its basic form, PHABSIM comprises two sets of procedures, hydraulic simulation and habitat simulation, using some 240 computer programs that are largely housed within five different hydraulic and five habitat simulation models. The results of the simulation procedures are linked to produce an output of Weighted Usable Area (WUA) versus discharge, showing losses or gains in habitat, described by some combination of depth, velocity, substratum and cover, as a function of discharge for the target species, lifestages or species assemblages of concern. Breakpoints on the WUA-discharge curves are used to recommend environmental flows.

Originally IFIM was developed for addressing the EFRs of economically important fish species (see Orth & Maughan 1982; Stalnaker *et al.*, 1996; *inter alia*). More recently, it has been adapted for other purposes: for assessment of instream flows for benthic invertebrates (Gore 1987; Campbell 1991; King & Tharme 1994); for instream biota downstream of hydropower projects (Gore *et al.,* 1989; Gore *et al.,* 1990a); for wildlife (Gore *et al.,* 1990b); for riparian vegetation (Bovee 1982; R. Milhous, Midcontinent Ecological Science Center, U.S. Geological Survey, U.S.A., pers. comm.); for flushing flows (Milhous e*t al.,* 1982, cited in Reiser *et al.,* 1989b); and for maintenance of water quality (Armour & Taylor 1991).

Other habitat simulation methodologies

Recently, several other habitat simulation models and methodologies of similar character and with many of the same data requirements as the PHABSIM component of IFIM have emerged (Dunbar *et al.*, 1998; Tharme 1996, 1997a, 2000). Several authors consider these various methodologies to have future potential, both in their countries of origin and abroad.

The first of these is the **River Hydraulics and Habitat Simulation Program** (RHYHABSIM; Jowett 1989; Jowett & Richardson 1995), developed in New Zealand. It is essentially a simplified version of PHABSIM, represented by a single computer program. It possesses a similar, though somewhat reduced, scope for application, has similar data requirements and comprises the same kinds of procedures. Its limitations relative to PHABSIM are detailed in Gan & McMahon (1990b) and summarised in Tharme (1996). The **Riverine Habitat Simulation Program**, RHABSIM, is a commercial version of PHABSIM, developed in the U.S.A. by Thomas R. Payne & Associates, that enables fully integrated river hydraulics and aquatic habitat modelling in a Windows environment (Dunbar *et al.*, 1998; Payne & Associates web site 2000). The **Computer Aided Simulation Model for Instream Flow Requirements** in regulated streams (CASIMIR; Jorde 1996) is a habitat simulation methodology that is being developed for assessment of instream flows under conditions of hydropower. Currently, it comprises a set of four basic computer models that, in combination, generate relationships between temporal and spatial patterns in river bottom shear stress and changes in discharge. The modelled available habitat is linked with habitat suitability curves for invertebrate species, where habitat is described by Statzner hemisphere values as indices of shear stress (Statzner & Higler 1986; Statzner *et al.*, 1988) (Jorde 1996, provides details), and EFRs are made on the basis of the modelled relationships. The **River System Simulator** (RSS) is a habitat simulation program system developed in Norway for specific application to rivers regulated by hydropower schemes (Alfredsen 1998). The RSS provides for the integration of several well established hydrological, hydraulic and habitat simulation models, for spatially and temporally dynamic habitat modelling (Alfredsen 1998). The **Riverine Community Habitat Assessment and Restoration Concept** (Nestler *et al.*, 1994, cited in Richter *et al.*, 1997) is considered a variant of IFIM that provides a means of identifying a flow regime that results in a similar spatial distribution of depth and velocity conditions to that occurring before impoundment. The French **Evaluation of Habitat Method** (EVHA; Ginot 1995, cited in Dunbar *et al.*, 1998) and Canadian microhabitat modelling system **HABIOSIM** (Dunbar *et al.,* 1998) are other habitat simulation methodologies bearing some resemblance to PHABSIM.

3.4.3 General strengths and deficiencies of current habitat simulation methodologies

Strengths

As habitat simulation methodologies are able to assess the impacts on physical habitat of incremental changes in flow, and typically have dynamic hydrological and habitat time series components, they can be used to examine a variety of alternative environmental flow scenarios for several species, lifestages and/or assemblages. Moreover, as they are computer-based, they are able to efficiently process large amounts of hydrological, hydraulic and biological data in a standardised yet flexible, interactive manner. Hydraulic and habitat modelling are performed at a scale that is relevant to the instream biota. In addition, the outputs are produced at increasingly high degrees of spatial and temporal resolution, particularly as advances are made in the field of multidimensional hydraulic modelling. Such modelling more accurately reflects the hydraulic conditions that are experienced by the biota and by different types of rivers (e.g. see Ghanem *et al.*, 1996).

Modelling approaches like PHABSIM are sufficiently flexible to enable alternative hydraulic variables to be incorporated in future, provided that they can be objectively quantified and that the way their influence changes with increments in discharge can be accurately modelled (Shirvell 1986). The methodologies are also highly adaptable (Tharme 1997a). For example, IFIM has been modified for and applied in several new contexts in recent years, such as environmental flows for peaking hydropower and sediment flushing. Advances are being made in linking the outputs from habitat simulation methodologies with current water quality and temperature models in more structured and sophisticated ways (Williamson *et al.,* 1993, provide an example for PHABSIM). IFIM is being integrated with models of biological populations, more complex suitability criteria and biological response models, to increase its potential for ecological prediction (Gore *et al.,* 1990a; Williamson *et al.,* 1993). The extent to which other habitat simulation methodologies are undergoing similar advancements is not well documented. However, CASIMIR includes modules for time series analysis and economic analysis. Moreover, habitat simulation approaches can be incorporated readily as tools within holistic type environmental flow methodologies (Tharme 1996; see Section 3.5).

Habitat simulation methodologies provide a means of assessing environmental flows in situations where competition between instream and offstream uses is likely to be highly controversial (Estes 1996), or where the river system and/or some its components are of exceptional conservation importance (Tharme 1996).

A few of the methodologies, most notably IFIM, have been subjected to several testing, verification and validation studies (Armour & Taylor 1991). It is also noteworthy that IFIM is the only methodology that is considered legally defensible in the U.S.A., and it is endorsed for EFAs currently, by the U.S. Fish and Wildlife Service.

Deficiencies

The focus in habitat simulation methodologies is mostly on target or key indicator species, with all its attendant problems (see Tharme 1996). With complex and highly diverse species assemblages, no single environmental flow recommendation can be used to address even a small proportion of the overall community (Prewitt & Carlson 1980). Most notably, however, where the aim of an EFA is to maintain a healthy river, as is often the case, the selection of appropriate target species is difficult. Moreover, virtually nothing might be known of the riverine biotas in many countries (Richardson 1986; Gan & McMahon 1990a; King & Tharme 1994). Although the methodologies are sufficiently flexible to be applied for many species and activities, they cannot be readily used yet for certain components of the riverine ecosystem, such as riparian vegetation, and do not attend to issues pertaining to long-term geomorphological change of rivers. Indeed, despite the fact that habitat simulation methodologies are resource-intensive and require considerable multidisciplinary specialist expertise, they represent only one of a suite of tools required for a complete EFA.

It is an assumption common to the majority of habitat simulation methodologies, that modelling biological response to discharge-related changes in physical microhabitat, as described by various hydraulic variables, is an adequate level at which to address EFRs for instream biota (Mathur *et al.*, 1985; Shirvell 1986). Such an assumption is likely to be highly limited or even inappropriate. The placement and number of cross-sections is also critical in determining the representation and reliability of the subsequent hydraulic and habitat simulations (Bovee & Milhous 1978), and yet it is often highly problematic (see King & Tharme 1994, for examples). Additionally, several specific problems exist in adequate measurement of the instream variables used for prediction of available physical microhabitat (see Tharme 1996).

Gore & Nestler (1988), and King & Tharme (1994) consider the use of accurately derived, species habitat suitability index (HSI) criteria to be one of the greatest constraints to proper implementation of habitat simulation approaches, as there are numerous potential sources of error and biases associated with curve construction and application. The transferability of HSI criteria from reach to reach, between rivers, for different seasons, or for the same species for different rivers, regions or countries, may be highly limited, and yet this factor is frequently overlooked in applications of methodologies like IFIM. Although approaches like IFIM were initially developed for application to specific rivers, they have since been applied worldwide to a vast number of different types of river with different hydraulic, geomorphological and hydrological characteristics. The indiscriminate use of methodologies in situations other than the ones for which they were developed potentially is highly problematic.

As the habitat simulation models are computer-based, there is considerable potential for their misuse by persons without proper training, as applications can be run without adequate understanding of the implications of various data input or output options. The high degree of complexity of most habitat simulation methodologies renders them difficult to comprehend or use, and extensive time and effort must be expended at the outset before suitable outputs can be obtained. Selection of appropriate models or subroutines also requires combined hydrological, hydraulic and ecological expertise unlikely to be present in a single user (Gan & McMahon 1990b; King & Tharme 1994). Researchers in isolation from the main areas of use and development of specific methodologies find it difficult to keep abreast of new developments or constraints to their application. With continual development and updating of these methodologies, there is the potential for confusing redundancies in the approaches and lack of adequate guidelines; such problems have already been experienced by IFIM users (Tharme 1996). Moreover, many current habitat simulation approaches are still in fairly early stages of development and require further refinement, as well as rigorous testing, validation, and follow-up monitoring (Armour & Taylor 1991; Tharme 1996).

3.5 HOLISTIC METHODOLOGIES

3.5.1 The nature and status of holistic methodologies

An holistic, ecosystems approach to EFAs is heralded by many environmental flow researchers as one of the major future directions of advancement in the science (Tharme 1996; Dunbar *et al.*, 1998; Arthington 1998a). In such an approach, important and/or critical flow events are identified in terms of criteria such as flow magnitude and timing, for all components or attributes of the riverine ecosystem.

Presently, there appear to be at least nine structured, distinctly holistic methodologies that are internationally recognised (Section 3.5.2; Tharme 1996, 2000; Dunbar *et al.*, 1998; Arthington 1998a), although several other approaches include holistic elements (see Tharme 2000). Two of these holistic environmental flow methodologies have been developing in parallel since 1991, from a common conceptual origin namely, the South African BBM and the Australian Holistic Approach (Arthington *et al.*, 1992). Historically, these methodologies have provided much of the impetus for the development of other holistic approaches over the past decade (Tharme 1996). Reviews of holistic methodologies in the international literature include those by Growns & Kotlash (1994); Tharme (1996, 1997a, 2000), Dunbar *et al.* (1998) and Arthington (1998a).

3.5.2 Current holistic methodologies

The Building Block Methodology

The BBM is introduced in King & Tharme (1994) and King (1996), and is comprehensively described in Tharme & King (1998), and King & Louw (1998). As the focus of this manual, the methodology is described in detail in Chapter 5 and others, and is therefore only briefly summarised below. The methodology is under ongoing development, and has been applied routinely only in South Africa, with a single application in Australia in 1996 (Arthington & Lloyd 1998).

Briefly, the methodology is based on the concept that some flows within the complete hydrological regime of a river are more important than others for maintenance of the riverine ecosystem, and that these flows can be identified, and described in terms of their magnitude, duration, timing, and frequency. In combination, these flows constitute the EFR as a river-specific modified flow regime, linked to a predetermined future state. A number of specialists in a workshop situation use hydrological baseflow and flood data, including various hydrological indices, cross-section based hydraulic data, and information on the flow-related needs of ecosystem components, to identify specific flow elements for the EFR. The process by which important flows are identified for various components of the riverine ecosystem, such as water quality and riparian vegetation, is documented in Chapter 5. These requirements are then built into modified flow regimes for both maintenance and drought conditions. Following the BBM Workshop, further routines allow for linking of the EFRs to current catchment climate and reservoir models, hydrological yield analyses and Scenario Meetings (King & Louw 1998).

The Holistic Approach

The origins, concepts and theoretical basis of the Holistic Approach are described in Arthington *et al.* (1992), Tharme (1996) and Arthington (1998a), and the methodology is reviewed in Growns & Kotlash (1994), Tharme (1996, 2000), Dunbar *et al.* (1998) and Arthington (1998a).

As the Holistic Approach developed in parallel with the BBM, it shares its basic tenets and assumptions (see King 1996, and above), and the EFR objectives rely on an equivalent of DS (Arthington & Lloyd 1998). As with the BBM, the basis of the Holistic Approach is the systematic construction of a modified flow regime, on a month-by-month and element-by-element basis (Arthington 1998a). Each element represents "a well-defined feature of the flow regime intended to achieve particular ecological, geomorphological or water quality objectives in the modified river ecosystem" (Arthington & Lloyd 1998). In a similar fashion to the BBM, the Holistic Approach relies on the use of historical flow records to serve as a coarse filter for defining elements of the natural flow regime for possible incorporation into a modified regime. It also incorporates various hydrological indices, such as percentiles from FDCs, and indices of predictability, constancy and seasonality of monthly flows. For example, monthly flow percentiles may be used to define sets of boundary conditions for drought, average and wet years. As in the BBM, the ways in which the various elements of the flow regime influence riverine habitat, aquatic biota and ecological processes are assessed, by examination of some of the key functions of baseflow and flood events, for instance for fish migration or for maintenance of natural channel dimensions. A computer program, ADVICE (Pusey and Flanders unpubl.) may be used to calculate the historic frequencies and durations of ecologically significant flow events.

In contrast to the BBM, the Holistic Approach does not yet comprise a fully documented, structured framework that can be applied routinely in EFAs (Tharme 1996). However, many conceptual and practical elements of the Holistic Approach have been incorporated into management strategies based on environmental flows throughout Australia, as well as into other methodologies like the Flow Restoration Methodology (FLOWRESM) (Arthington 1998a, b; see below).

The Downstream Response to Imposed Flow Transformations Methodology

The DRIFT Methodology was very recently developed in southern Africa for use in the Palmiet IFR study (Brown *et al.,* 2000) and Lesotho Highlands Water Project (Brown & King 1999, 2000). It is an interactive, top-down holistic approach based on the same conceptual tenets and multidisciplinary, workshop-based interaction as the BBM and Holistic Approach (King *et al*., 1999; Tharme 2000). However, it focuses on the identification of a series of river water levels associated with a particular set of biophysical functions and of specific hydrological and hydraulic character. Specialists in each discipline describe the consequences of reducing discharges through these identified flow bands and their thresholds, in terms of deterioration in biotic and abiotic condition. The identification of the 'minimum degradation' reduction level and its consequences typically provides the starting point for the process. Once a wide range of flow reductions has been assessed, there is considerable scope for the comparative evaluation of a vast number of EFR scenarios, each reflecting the presence or absence of different flow bands with attendant consequences. Furthermore, in DRIFT, the links between social consequences, which are evaluated alongside ecological and geomorphological ones, and economic costs are explicit and comprehensive (Brown & King 1999).

The methodology is currently under development and there is, as yet, no published guide to its procedures. Tharme (2000) provides the only review of DRIFT to date.

The Expert Panel Assessment Method

The Expert Panel Assessment Method (EPAM) was the first multidisciplinary, panel-based approach to EFAs employed in Australia (Arthington 1998a), developed jointly by the New South Wales departments of Fisheries and Water Resources (Swales *et al.*, 1994; Swales & Harris 1995). Growns & Kotlash (1994), Tharme (1996, 2000), Dunbar *et al.* (1998) and Arthington (1998a) provide reviews of EPAM.

The method aims to address river ecosystem health, rather than the health of single components, although the "suitability of streamflows for the survival and abundance of native fish is taken as the primary criterion of the suitability of the discharge as an environmental flow" (Swales & Harris 1995). It relies on ecological interpretation, by a panel of experts in aquatic ecosystems and river management, of multiple trial flow releases from an impoundment, at one or a few downstream sites on the study river, for the recommendation of a modified flow regime (Swales & Harris 1995). In the first application of EPAM to identify EFRs for six tributaries of the Murray Darling system, two multidisciplinary expert panels, each comprising a freshwater fish ecologist, riverine invertebrate ecologist and fluvial geomorphologist, visually assessed four different flow releases independently, and on seasonal and non-seasonal bases (Swales & Harris 1995). The releases represented the 80%, 50%, 30% and 10% FDC percentiles for each river site. For each release, flow suitability was ranked on a scale of 1 (poor) - 5 (excellent), with assessment criteria focused on suitability of the flows for fish survival and abundance, invertebrate productivity and habitat quality. The final scores and recommended environmental flows, as percentiles, were based on panel consensus, as illustrated in Swales & Harris (1995).

The Scientific Panel Assessment Method

The Scientific Panel Assessment Method (SPAM) is an Australian holistic methodology that was developed during the Barwon-Darling environmental flow study (Thoms *et al.*, 1996). It is considered a more sophisticated version of EPAM, in which key features of the ecosystem and hydrological regime and their interactions at multiple sites are used as the basis for flow assessment (Thoms *et al.*, 1996; Arthington 1998a). In terms of its philosophy and methodological procedures, SPAM also shares many features with the Holistic Approach and BBM (Thoms *et al.*, 1996).

In order to determine the EFR, a panel of experts address five main ecosystem components for which "management performance criteria" can be identified: fish; trees; macrophytes; invertebrates; and geomorphology. The criteria are applied for three elements (and associated "descriptors") identified as exerting an influence on the ecosystem components, namely flows regime (i.e. climate-driven, long-term flood/drought cycles), individual hydrographs (i.e. flow events) and physical structure (see Thoms *et al.*, 1996, for further explanation). As with the BBM and Holistic Approach, there are field visits to multiple sites, and all available data on the various ecosystem components are collated. A cross-tabulation, workshop-based approach is employed to identify links between the ecosystem components and elements. The broad-scale ecosystem linkages are then applied to specific levels of flow, and in some cases, to specific river reaches, for instance using cross-section hydraulic data in the identification of important flow thresholds as FDC percentiles. Once the most important features of the hydrological regime have been identified, the degree to which they have been altered from natural by the water-resource development is assessed and the implications of the changes for the riverine ecosystem are analysed. Simulated hydrological data from the **Integrated Quantity Quality Model** (IQQM; see below), a generic daily hydrological simulation modelling platform (Arthington 1998a), in conjunction with historical flow records are used for these purposes. Finally, a series of management principles and general recommendations, as well as specific, though often qualitative, flow recommendations are presented.

The Habitat Analysis Method and Water Allocation Management Planning Benchmarking Procedure

The Habitat Analysis Method

The Habitat Analysis Method, developed by the former Queensland Department of Primary Industries, Water Resources (now Department of Natural Resources) as part of the Water Allocation and Management Planning (WAMP) initiative, evolved as an extension of expert panel-based holistic methodologies like EPAM and SPAM (Walter *et al.*, 1994; Burgess & Vanderbyl 1996, cited in Arthington 1998a; Burgess & Thoms 1997, cited in Arthington 1998a; Burgess & Thoms 1998). The method's primary role is as a planning tool for water-resource development at a whole-catchment scale (Arthington 1998a). In its initial form, the Habitat Analysis Method, which has similar tenets to the BBM and Holistic Approach, uses habitat as a surrogate for assessing the flow requirements of aquatic biota and does not focus directly on the needs of individual target species or communities (but see below).

The set of procedures used to derive the EFR is focused on a specialist Technical Advisory Panel (TAP) workshop involving experts possessing disciplinary and/or local knowledge of the study catchment (Arthington 1998a). Prior to the TAP workshop, data are collated including information on the current hydrological and ecological condition of the study river system. In the workshop, generic habitat types existing within the catchment, ranging from riffles to wetlands and the estuarine zone, are identified. A matrix of the habitat types linked to their critical flow-related ecological requirements is generated, bypass flow strategies to meet the EFR are determined and lastly, a monitoring strategy is devised (Arthington 1998a). After the workshop, the individual environmental flows identified in the workshop are quantified in terms of volume, discharge, duration and seasonal timing (Arthington 1998a). The impact of providing each environmental flow option is then assessed by considering its effectiveness in meeting critical environmental requirements, water resource entitlements and the capacity of infrastructure outlet works, as debated during consultations with stakeholders (Burgess & Vanderbyl 1996, cited in Arthington 1998a). Thereafter the adjusted EFR is fine-tuned by the TAP and included in the water management plan for the river.

The Water Allocation and Management Planning Expert Panel Method incorporating benchmarking

More recently, the WAMP initiative has evolved beyond the Habitat Analysis Method *per se*, as the "WAMP Expert Panel Method" (Arthington 1998a) to more explicitly focus on the flow requirements of the whole riverine ecosystem. The tenets and procedures employed exhibit many similarities with those of the BBM, Holistic Approach, SPAM and DRIFT (Burgess & Thoms 1997; DNR 1998a, 1998b; cited in Arthington 1998a; Burgess & Thoms 1998; Vanderbyl 1998). Although habitat remains a crucial indicator of ecosystem health, critical flow thresholds and ranges of flows to maintain various habitats are addressed alongside those flows required by selected communities/species, for purposes such as flushing sediments, as well as for ecosystem components like the floodplain and riparian zone. The IQQM (see above) is used extensively within the TAP expert panel process to generate hydrological time series, both pre-regulation and reflecting various flow modification scenarios, as well as various statistical indicators of critical flow events. The latter statistics are used in a WAMP benchmarking procedure which is particularly applied in poorly studied systems (Bunn 1998). Calculated changes in flow statistics are linked to degrees of ecological degradation to produce ‘benchmarks’ for comparison with the same statistics calculated for the study river’s natural flow regime or for other rivers of similar hydrology. The percentage change from natural can be determined and interpreted from an ecological perspective (Arthington 1998a). In combination, the IQQM and benchmarking procedure enable structured assessment of alternative environmental flow scenarios (Burgess & Thoms 1998; DNR 1998a, b; Vanderbyl 1998).

The Flow Restoration Methodology

The FLOWRESM, developed in Queensland, Australia, during an EFA for the Brisbane River downstream of Wivenhoe Dam, is aimed specifically at addressing EFRs in river systems exhibiting a long history of flow regulation and requiring restoration (Arthington 1998a). In essence, FLOWRESM represents a hybrid of the Holistic Approach and the BBM, where the emphasis in the identification of the essential features of the hydrological regime is on those flows that need to be built back into the regime to shift the regulated river system in the direction of the pre-regulation state (Arthington 1998a, b; Tharme 2000).

Arthington (1998a) describes the main activities occurring in an application of FLOWRESM. Basically, the environmental impacts of historical and current flow regulation are ascertained by a multidisciplinary range of specialists in geomorphology, river hydrology and hydraulics, water quality and aquatic ecology. The identification of options for the provision of the EFR downstream of the dam then takes place during an Environmental Flow Workshop, after which alternative environmental flow scenarios are modelled and evaluated. The IQQM (see above) is employed at several stages in the overall process, from generation of the river’s unregulated hydrological regime through to determination of the characteristics of the regulated flow regime under various environmental flow and water management scenarios (Arthington 1998a). Options for the provision of the EFR, given existing and future constraints on the river system, are reviewed, and consideration is given to alternative approaches and infrastructure arrangements to assist with its provision. The development of a monitoring strategy, and the identification of factors other than flow regulation that may influence river condition and consideration of remedial actions, are also integral to the process.

The River Babingley Method

Petts (1996) and Petts *et al.* (1999) describe an holistic approach to define an “Ecologically Acceptable Flow Regime” (EAFR), developed specifically for application in groundwater-dominated rivers in the Anglian Region of England. It was originally referred to as the River Wissey Method (G. Petts, University of Birmingham, pers. comm.), but now is more commonly known as the River Babingley Method (Dunbar *et al.,* 1998), after its first published application on the River Babingley (Petts & Bickerton 1994, cited in Petts *et al.,* 1999). The method relies on an ecological assessment of the study river and specification of ecological objectives comprising specific targets, such as the provision of spawning habitat for trout in autumn or wetland habitats in spring for riparian species. Four general benchmark environmental flows, termed “Threshold”, “Adequate”, “Desirable” and “Optimum” ecological flows, are identified

(Petts *et al.,* 1999). For example, the “Threshold Ecological Flow” may be defined as that flow which sustains a few habitat refuges, and below which level all habitat for a target species will be lost. Two higher benchmark flows (floods), a “Channel Maintenance Flow” and “Habitat Maintenance Flow” are also determined for geomorphological and sediment flushing purposes. The various flows are used to construct “Ecologically Acceptable Hydrographs”, which may include provisions for wet years and drought conditions, in a process that resembles that of the BBM and Holistic Approach. Ecologically acceptable flow frequencies and durations are assigned to the hydrographs, which are then combined to produce an FDC representing the EAFR.

Flow Management Plan

The Flow Management Plan (FMP) was developed in South Africa, through the Institute for Water Research (IWR), Rhodes University, for specific use in highly regulated river systems that will need to continue to be managed in such a state in the future. Although the procedures comprising the FMP Method have not been formally documented as yet, they are described in three case applications of the FMP to local rivers (Muller 1996, 1997). The FMP is discussed further in Section 4.6.4 of this manual, as it represents one of the methodologies for use within the framework of ecological Reserve determination.

The first step in the FMP is the definition of so-called ‘Operable Reaches’ for the study river, and the selection of sites within these reaches. Current operating rules are also clearly established up front, where possible, in a multidisciplinary workshop environment, so that critical and non-negotiable criteria are known for each of the reaches. The next step is the determination of the current ecological status of the river, for each site within each operable reach. The process entails the classification of the Present Ecological State (PES) of each site, and then the definition of its DS. The flows needed to meet the DS are subsequently determined in a similar manner to that of the BBM (see above), on the basis of the various ecological requirements of the biota and other ecosystem components, for baseflows and floods. As in the BBM, the issues of flow magnitude, timing, duration, frequency and natural flow variability are addressed. Ongoing feedback is provided during the environmental flow workshop by system operators as to whether the recommended flows are possible under current operational constraints, before final environmental flow recommendations are made.

3.5.3 Strengths and deficiencies of holistic methodologies

Holistic methodologies exhibit several advantages over other types of environmental flow methodology, most importantly in that they can potentially be used to address all components of the riverine ecosystem (Growns & Kotlash 1994; Tharme 1996), and have strong links with the natural hydrological regime. Also, they incorporate biological, geomorphological and hydrological data, and consider all aspects of the flow regime, such as the magnitude and timing of both baseflow and flood events. Their outputs can be generated at several levels of resolution (e.g. month-by-month discharges, percentages of virgin/present Mean Annual Runoff (MAR), and virgin/present monthly percentiles from FDCs; Tharme 1996; Thoms *et al.*, 1996). Hence, they are pragmatic, flexible and robust, as well as transparent. They were originally designed to cope with EFAs where time, finances, available data and expertise were constraints. As such, they rely to a considerable extent on professional judgement, so care must be taken to apply them in a rigorous, well-structured manner, in order to ensure sufficiently reproducible results. However, they can equally be applied in both data poor and data rich situations, with the confidence level of the outputs increasing with increasing data and understanding of the river. The methodologies are firmly based on South African and Australian experiences of variable climate and hydrology, heterogeneous geomorphology, and of limited available information on biological flow dependencies of riverine biota (Growns & Kotlash 1994; Tharme 1996).

As with most other current environmental flow methodologies, there are few applications of holistic methodologies other than in their place of origin. However, they are starting to attract considerable international interest (Tharme 1996, 2000; Dunbar *et al.,* 1998; Arthington 1998a). The methodologies all require comparison with other international approaches, testing and verification of their assumptions, and assessments of their predictive capacity. Although detailed physical habitat and water quality modelling are not routinely performed in holistic methodologies to date, there is scope for the advancement of these methodologies through the progressive incorporation of such tools (Tharme 1996). In relation to the BBM, hydrological models for applying the recommended modified flow regime dynamically over time (years) are in the first stages of development (see Chapter 22). Such models will allow the flexibility essential for coupling the recommended regime with natural climatic events at a number of temporal scales, in order to introduce variability into the recommended modified flow regime. In the case of the BBM particularly, the methodology is sufficiently structured, has documented guidelines, and has been applied routinely on enough occasions, that practitioners can be trained in its future application. A BBM protocol for monitoring the recommended flow regimes is in the early stages of development. Furthermore, the BBM is formally endorsed by DWAF, and is institutionally accepted by other South African water management and conservation organisations. Certainly, as a group, holistic methodologies exhibit considerable potential for further advancement, although many are still in their formative stages.

3.6 METHODOLOGIES FOR ASSESSMENT OF FLUSHING FLOW REQUIREMENTS

3.6.1 The nature of flushing flow methodologies

Channel maintenance or flushing flows are critically important for the maintenance of several geomorphological and sedimentological characteristics of river channels (see Reiser *et al.,* 1989b, and Tharme 1996, for further information). Nevertheless, the recommendation of such flows is one of several facets of EFAs which has not been adequately investigated. The topic of flushing flows is explored at length in Reiser *et al.* (1987, 1989b) and more recently in Brizga (1998).

3.6.2 Types of methodology

Limited research has been conducted to develop methodologies to determine the magnitude, timing, frequency, duration and effectiveness of flushing flows (Wesche *et al.,* 1987). Most methodologies have focused on the maintenance of fish habitat (Reiser *et al.,* 1989b), while others have primarily been developed for different environmental flow purposes, but have components that can be used to address requirements for flushing flows (see below).

Methodologies for the establishment of flushing flow recommendations can be separated into five broad categories: hydrological event methods; channel morphology methods; sediment transport mechanics methods, which include the majority of available methods; habitat simulation methodologies, specifically IFIM; and holistic methodologies (Tharme 1996). Tharme (1996) reviews the basic data requirements, advantages and disadvantages of 23 methods within these various categories. Reiser *et al.* (1987) suggest using both an office and field method for determining flushing flows, with the office method producing an initial estimate for refinement using field evaluations.

More recently and, to date, generally in South Africa and Australia, holistic methodologies have tended to be the main avenue by which flushing flows and flows for other geomorphological purposes have been calculated (Section 3.5). For example, the use of the BBM for this purpose is illustrated in Chapter 14.

3.6.3 Critique of flushing flow methodologies

The strengths and weaknesses of specific methodologies are summarised in Tharme (1996) and Brizga (1998), while some more general problems associated with flushing flow methodologies are provided below.

Presently, there is no recognised standard or state-of-the-art office or field methodology for the prescription of flushing flows (Reiser *et al.,* 1987), and many uncertainties are associated with existing approaches. Most flushing flow recommendations are largely made on the basis of professional judgement, and follow-up or verification studies generally are not undertaken. Of the three component-specific types of methods, Hey’s (1981, cited in Reiser *et al.,* 1989b) observation of test flow releases is considered the most reliable one, and where test releases cannot be made, sediment transport methods previously have been advocated. Although no single methodology entirely addresses the required magnitude, duration, effectiveness, timing and frequency of flushing flows, it would seem that holistic methodologies presently provide the greatest scope for such a comprehensive assessment. The documented variability of results generated by different flushing flow methodologies (Tharme 1996, cites examples) amplifies the importance of monitoring studies. These are the only way in which the adequacy of the recommendation can be verified, and the effectiveness and reliability of the method assessed.

3.7 METHODOLOGIES FOR ASSESSMENT OF ENVIRONMENTAL FLOW REQUIREMENTS OF RIPARIAN VEGETATION

3.7.1 Available environmental flow methodologies for riparian vegetation

Prior to the 1980s, there was little emphasis on the development of this aspect of environmental flow assessment, and most relevant methodologies have been developed during only the past decade (Tharme 1996). Currently, there are four main, often partly integrated, ways in which EFRs for riparian vegetation are assessed.

The first approach entails the linkage of stream discharge and various related hydrological variables with variables associated more directly with the riparian belt, particularly the riparian water table; an indirect link is then sometimes established between the latter variables and the vegetation. Kondolf *et al.*’s (1987)

‘Hydrogeomorphic Site Characterisation Methodology’, summarised in Tharme (1996), is an example of this type of approach.

Flow-vegetation growth models represent the basis of a second set of techniques, of which Stromberg & Patten’s two kinds of dendro-ecological environmental flow models are examples (Stromberg & Patten 1990, 1996). Model data requirements, applications, advantages and disadvantages of the two approaches are summarised in Tharme (1996).

The third kind of approach is the assessment of riparian vegetation as an ecosystem component within an holistic methodology. For example, the use of the BBM for this purpose is illustrated in Chapter 16. The data requirements, applications, advantages and disadvantages of using such methodologies for environmental flows for riparian vegetation are given in Tharme (1996, 2000) and McCosker (1998), among others.

Finally, some of the current advances in habitat simulation methodologies, notably IFIM (R. Milhous, pers. comm.) and CASIMIR (Section 3.4), are aimed at incorporating riparian zone models.

3.7.2 Critique

Presently, holistic methodologies like the BBM and DRIFT appear to be the best structured of all methodologies for assessing EFRs for riparian species and/or communities (Tharme 1996, 2000). However, considerable research is required to improve the level of understanding of relationships between riparian vegetation and river flow, if appropriate methodologies are to be developed for routine application.

3.8 METHODOLOGIES FOR ASSESSMENT OF ENVIRONMENTAL FLOW REQUIREMENTS OF RIPARIAN AND INSTREAM WILDLIFE

3.8.1 Available environmental flow methodologies for riparian and instream wildlife

The field of environmental flow methodologies for riparian (terrestrial) and instream wildlife has been much neglected relative to the development of methodologies for other purposes. To date, applications of methodologies providing environmental flows for wildlife have been few worldwide, and there is considerable potential for advancement in this field (Tharme 1996, 2000).

Currently, there are two main avenues of development of methodologies for wildlife. The main trend has been the case-specific use of predictive wildlife models based on relationships between habitat and discharge (see Tharme 1996, for examples). Most commonly, this has involved application of IFIM (Section 3.4), through the development of SI curves describing habitats upon which various wildlife species are dependent (e.g. Mosley 1983; Gore *et al.*, 1990b).

Recently, some EFAs performed using the BBM, Holistic Approach and DRIFT, *inter alia* (Section 3.5), have included considerations of use by wildlife (e.g. Tharme 1997b, c; Arthington 1998a). Although holistic methodologies have the potential to include environmental flows for wildlife in a structured manner, this is not routinely done at present (Tharme 1996, 2000).

3.8.2 Critique

Inadequate emphasis is presently being placed worldwide on research into environmental flows for wildlife, and there are several areas where research is required for the advancement of methodologies (see Tharme 1996, 2000, for details). Holistic methodologies have considerable potential for the inclusion of riparian and instream wildlife as an integral component of the riverine ecosystem (Tharme 1996).

3.9 METHODOLOGIES FOR ASSESSMENT OF ENVIRONMENTAL FLOW REQUIREMENTS FOR WATER QUALITY PURPOSES

3.9.1 Available environmental flow methodologies for water quality purposes

The majority of environmental flow methodologies to date have focused entirely on flow quantity and water quality has often been disregarded, despite its obvious importance (Tharme 1996; Malan & Day 2002). Currently, there are three commonly used general approaches for assessing environmental flows for water quality purposes (Tharme 1996, 2000).

Firstly, and most commonly, several sophisticated water quality models have been developed for application to regulated rivers (see Zimmerman & Dortch 1989, and Malan & Day 2002, for examples). However, links between model outputs and flow within EFAs are often not explicit, few guidelines are available, and professional judgement is required (Tharme 1996). The CE-QUAL-RIV1 (Bedford *et al.,* 1983, cited in Dortch & Martin 1989) is an example of a water quality model with scope for application in EFAs.

The second approach entails the application of habitat simulation methodologies (Section 3.4). Specifically, IFIM has been used to assess environmental flows for water quality in one of two ways. First, various water quality and temperature models have been linked with the other components of IFIM (Brown & Barnwell 1987, cited in Armour & Taylor 1991). Secondly, SI curves have been constructed for temperature and water quality variables, where the curves are related to specific activities of riverine biota and can be incorporated directly into PHABSIM (Milhous *et al.,* 1989; Armour & Taylor 1991).

Holistic methodologies (Section 3.5) have also been used to assess environmental flows for water quality or related social purposes (Tharme 1996; King 1996; Arthington 1998a). For instance, there are several documented cases in which water quality has been addressed within the BBM (Tharme 1997a), and its application for this purpose is described in Chapter 15. However, in many instances the link with water quantity (as discharge) is weak in holistic methodologies. It will remain so until water quality modelling becomes a structured part of the methodology and this can be linked to much better data than presently exist on the ranges of tolerance for aquatic species to water quality variables (Tharme 1996).

3.9.2 Critique

Holistic methodologies, like the BBM and DRIFT, have considerable potential for assessment of EFRs for water quality, while IFIM and similar habitat simulation methodologies also provide suitable approaches (Tharme 1996, 2000). Future efforts to include water quality more comprehensively within such methodologies should include modelling of present and projected future water quality conditions, and the establishment of links with the ranges of tolerance of aquatic species to water quality variables.

3.10 METHODOLOGIES IN USE OR RECOMMENDED FOR FUTURE APPLICATION IN VARIOUS COUNTRIES

Table 3.1 provides an overview of the international status of environmental flow methodologies, on a country-specific basis. Although the summary is not comprehensive and is in the process of being updated (Tharme 2000), it provides a first indication of international trends in approaches to the assessment of environmental flows. The majority of available information pertains to North America, which has historically been at the forefront of the field of EFAs. However, many of the methodologies developed there have limited application elsewhere in the world. As is evident in Table 3.1, in more recent years many other countries, especially in the Southern Hemisphere, have initiated the development of methodologies that may be more appropriate for local conditions.

3.11 THE PRESENT STATUS OF ENVIRONMENTAL FLOW METHODOLOGIES IN SOUTH AFRICA

3.11.1 Methodologies currently in use

Developments in EFAs in South Africa have advanced dramatically during the past decade (King & O'Keeffe 1989; Gore & King 1989; O'Keeffe & Davies 1991; Gore *et al.*, 1991; King & Tharme 1994; King *et al.*, 1995). Tharme (1996) and Tharme & King (1998) provide an overview of the historical, local evolution of environmental flow methodologies.

Recently, attention has been largely focused on the development of the holistic BBM and DRIFT (Section 3.5), as well as derivative approaches for determination of the ecological Reserve (see Chapter 4). Holistic methodologies are considered most appropriate for South African conditions, where there are constraints in terms of, *inter alia*, historical hydrological, ecological and geomorphological data on the river system of concern; limited finances; extreme time pressures with future water-resource development projects; and limited manpower and expertise. However, other approaches, like IFIM (Gore & King 1989; King & Tharme 1994; Gore *et al.,* 1990b) and the Biotope Approach (Rowntree & Wadeson 1996) (Table 3.1) have been used and show merit for further development and incorporation within holistic EFA frameworks (Tharme 2000).

3.11.2 A hierarchy of environmental flow methodologies for use in South Africa

Tharme (1996, 1997a) recommended a multi-scale approach to EFAs for South Africa, comprising a three-tier hierarchy of methodologies, with professional judgement being exercised at all levels (Figure 3.1). Although all levels of the hierarchy should preferably be applied at various stages within a major water-resource development, in all likelihood the third level would only be applied in cases of highly controversial projects and/or where the riverine ecosystem of concern is rated as of high conservation importance. The proposed hierarchy ties in closely with the types of methodologies and appropriate levels for their application that have been proposed, more recently, for ecological Reserve determination (see Section 4.6 & Table 4.3).

The broadest level of the hierarchy comprises reconnaissance-level assessments of environmental flow needs. Methodologies based primarily on hydrological indices, for example RVA (Section 3.2), would be most appropriate at this level.

Holistic methodologies would be most appropriate for application at the intermediate level of the hierarchy, the level at which the majority of routine EFAs is likely to be conducted. Tharme (1997a) recommends further advancement of the BBM for its most effective use at this level, for instance by incorporating ecologically relevant hydrological indices into the hydrological component and by biotope-level modelling (see Figure 3.1, for other examples). It is noteworthy that DRIFT, developed subsequently, incorporates early elements of both these features (Tharme 2000).

With rivers of high conservation priority, it would be appropriate to apply elements of a suitable, internationally recognised habitat simulation methodology (e.g. IFIM; Section 3.4 & Figure 3.1) within or in conjunction with an holistic methodology like the BBM or DRIFT, where the flow requirements of key, ecologically important or rare species need to be addressed. This would represent the final, most resource-intensive level of the proposed hierarchy. Considerable effort would need to be expended, however, in order to select the most appropriate techniques from the wide range available, and to train and guide researchers in the development and application of these techniques in a local context.

Table 3.1 **Environmental flow methodologies in use or recommended for future application in various countries (modified from Tharme 1997a). The most widely used or preferred methodologies are noted. Much of the information presented is derived from Reiser *et al.* (1989b), Growns & Kotlash (1994), Tharme (1996), Estes (1996), Dunbar *et al.* (1998), Arthington (1998a), Arthington & Zalucki (1998), and King *et al.* (1999). An updated synopsis is presented in Tharme (2000). (See list of acronyms).**

COUNTRY	**ENVIRONMENTAL FLOW METHODOLOGIES IN USE**	**MOST WIDELY USED OR PREFERRED METHODOLOGIES**	**COMMENTS**
Alaska	❖ IFIM; Tennant Method, including modifications thereof on the basis of professional judgement and fish data; various hydrological indices, including QAM and FDCA; others (unspecified)	❖ Tennant Method, or a modification thereof, is often routinely applied ❖ IFIM is used for special cases	❖ Holistic methodologies do not appear to have been applied ❖ Estes (1996) provides further information
Australia	❖ Various methodologies: IFIM; RHYHABSIM; Holistic Approach; Tennant Method; FDCA and various other hydrological indices; professional judgement; EPAM; SPAM; FLOWRESM; Habitat Analysis Method and WAMP benchmarking; MTA; BBM ❖ State-dependent	❖ IFIM and holistic methodologies	❖ Methodologies used by each state are detailed in Growns & Kotlash (1994), Tharme (1996); Stewardson & Gippel (1997), Dunbar *et al.* (1998), Arthington (1998a), and Arthington & Zalucki (1998)
Austria	❖ Habitat modelling; other methods unspecified	❖ Unspecified	❖ A future aim is to combine IFIM with elements of holistic methodologies ❖ An holistic framework has been proposed, including: expert opinion; a list of criteria; a 7-point naturalness scale; elements of IFIM, including PHABSIM ❖ A quantitative fish habitat modelling approach is under development
Britain and Wales	❖ Various methodologies: IFIM; hydrological tools (e.g. Micro LOW FLOWS); hydrological indices (e.g. Q95); Environmentally Prescribed Flow Method; hybrid and alternative approaches, including the Scott Wilson Kirkpatrick Method, Jones Peters Method, HABSCORE, RIVPACS, Biotopes/Functional Habitats methods; holistic methodologies, such as the River Babingley (Wissey) Method and expert panel approaches	❖ Unspecified	❖ A future aim is to combine IFIM/PHABSIM analyses for target species with holistic elements ❖ Holistic methodologies, specifically the Holistic Approach, BBM and EPAM are recommended for further investigation ❖ The Tennant Method could be modified to develop more multidisciplinary stream ecotype-specific methods, with extensive work and use of other methods in its development ❖ Hydrological indices, e.g. RVA and Texas Method, and regionalisation of seasonal FDCs, are considered useful for preliminary assessments, use on a river ecotype basis, and incorporation in existing methods (e.g. River Babingley Method) ❖ Other methods considered to have potential include: the Basque Method; CASIMIR; Biotopes/Functional Habitats approaches ❖ Further information on useful methodologies is provided in Dunbar *et al.* (1998)

Table 3.1 Continued.

COUNTRY	ENVIRONMENTAL FLOW METHODOLOGIES IN USE	MOST WIDELY USED OR PREFERRED METHODOLOGIES	COMMENTS
Canada	❖ Various methodologies: IFIM, including Biologically Significant Periods/Fish Rule Curve Approach; Tennant Method, including set percentages of Average Annual Flow (e.g. 25% MAF Method) and Tessman Modification; Wetted Perimeter Method; correlation of fish year class to spawning flow; WSP model; water quality models; 7Q10 Method; Median Monthly Flow Method; FDCA (e.g. 90th percentile); HABIOSIM	❖ IFIM used in all of the 7 provinces that apply environmental flow methodologies, and Tennant Method or a modification thereof often routinely applied	❖ Northwest Territories do not employ any methodologies ❖ Holistic methodologies do not appear to have been applied ❖ Methodologies used by each province are detailed in Reiser *et al.* (1989b), Tharme (1996) and Dunbar *et al.* (1998)
Czech Republic	❖ IFIM	❖ Unspecified	❖ IFIM-based procedures are under development
Denmark	❖ Hydrological methods	❖ Median Minimum Method	❖ It is recognised that other low flow hydrological indices are more sophisticated
Finland	❖ EVHA and detailed approaches based on physical habitat for fish species	❖ Unspecified	❖ There are no standard methods
France	❖ Habitat simulation methodologies, such as EVHA, AGIRE, ENSAT Toulouse Method	❖ EVHA: applied in about 70 cases	❖ Ongoing research is taking place into continuous fish population modelling within an IFIM framework
Germany	❖ Hydrological indices, case-specific expert opinion, and a habitat simulation methodology, CASIMIR	❖ Mean of minimum daily flows for each year, or a fraction thereof, and expert opinion have been used to assess 100 flows	❖ CASIMIR has been applied for benthic invertebrates as a benthic shear stress model, and new models are under development for fish habitat and riparian zone plant communities
Italy	❖ Hydrological indices, including FDCA, daily and annual mean flows; IFIM; Tennant Method; Wetted Perimeter Method; Singh Method, and Orth & Leonard Method for regionalisation; hybrid approach using regionalisation of Q_{95} on the basis of geology and catchment area	❖ Hydrological indices ❖ IFIM in resource-intensive applications	❖ Relationships between fisheries standing crop and environmental variables are under development
Japan	❖ IFIM, including multidimensional hydraulic modelling and multivariate habitat suitability criteria	❖ Unspecified	❖ None
Netherlands	❖ Hydrological model, PAWN; alternative approaches, including HEP, a general habitat suitability scoring model, an ecotope classification (ECLAS), a physical habitat model (MORRES), a habitat suitability model (EKOS), and a policy and alternatives analysis model (AMOEBA);HSI type model; hybrid methodologies based on habitat simulation, such as a GIS-based microhabitat model	❖ Unspecified	❖ None
New Zealand	❖ Various hydrological, hydraulic and habitat simulation methodologies (unspecified); IFIM; RHYHABSIM; Orth & Leonard Method for regionalisation, and other habitat regionalisation techniques	❖ RHYHABSIM: used on about 25 rivers; IFIM	❖ None
Norway	❖ Hybrid approaches based on habitat modelling, specifically RSS which includes the HEC-2 program, BIORIV I/II and HABITAT models, and temperature	❖ RSS and microhabitat modelling	❖ None

Table 3.1 Continued.

COUNTRY	ENVIRONMENTAL FLOW METHODOLOGIES IN USE	MOST WIDELY USED OR PREFERRED METHODOLOGIES	COMMENTS
South Africa	❖ Various methodologies: hydrological indices, including FDCA; IFIM; BBM; DRIFT; FMP; Bulk Water Estimate (BWE); MTA; some alternative approaches, e.g. River Conservation Status Model; geomorphological change-flow and riparian vegetation-flow models, Biotopes Approach; multivariate statistical techniques for hydrological and ecological regionalisation	❖ BBM and associated suite of methods for ecological Reserve determination	❖ The Biotopes Approach is recommended for further investigation, including biotope-level modelling within habitat simulation methodologies ❖ Habitat and water quality modelling techniques are recommended for incorporation into the BBM and DRIFT, and research into linking water quality and quantity is underway ❖ Research is taking place into the identification of ecologically-relevant hydrological indices ❖ The IFR Model and a link model to reservoir operation, WRYM, have been developed
Spain	❖ Hybrid and alternative methodologies, including an approach similar to IFIM with holistic elements and historical flow series, multivariate biomass models, Cubillo's Madrid Method, and the Basque Method; IFIM; hydrological indices, specifically the Basic Flow Method	❖ Unspecified	❖ A future aim is to combine IFIM with elements of holistic methodologies ❖ Dunbar *et al.* (1998) provide further information
Sweden	❖ RSS	❖ RSS	❖ Only two environmental flow studies have been completed
Switzerland	❖ Hydrological indices; expert opinion	❖ Unspecified	❖ A future aim is to combine IFIM with elements of holistic methodologies, especially incorporating floodplain ecological data
U.S.A.	❖ An extremely wide array of methodologies covering hydrology-based, hydraulic rating, habitat simulation, and various hybrid or alternative approaches; some methods unspecified ❖ 17 commonly used methodologies: IFIM; Tennant Method, with various regional adjustments accounting for local hydrological regimes and further modifications, e.g. Bayha Modification and Tessman Modification; Wetted Perimeter Method; ABF Method; 7Q10 Method; Professional judgement; R-2 Cross Method; hydrological methods based on flow records/FDCA; Water Quality methods; USGS Toe-Width Method; Arkansas Method; AVDEPTH program; HEC-2 program; HQI; Oregon Method; September Median Flow Method; Vermont Fish-Flow Method ❖ Others including: RCHARC; Texas Method; Habitat Evaluation Procedure (HEP); RVA; Singh Method, and Orth & Leonard Method for regionalisation ❖ State-dependent	❖ IFIM: used in 30 states and cited in majority of cases as the preferred methodology; requisite methodology in 3 states ❖ Tennant Method: used in 11 states; primary methodology in 3 states ❖ Wetted Perimeter; Average BaseFlow (ABF); 7Q10 are other 3 methodologies frequently applied	❖ Holistic methodologies do not appear to have been formally applied ❖ Methodologies used by each state are detailed in Reiser *et al.* (1989b) and Tharme (1996) ❖ Habitat modelling techniques, especially using PHABSIM, are under continual development

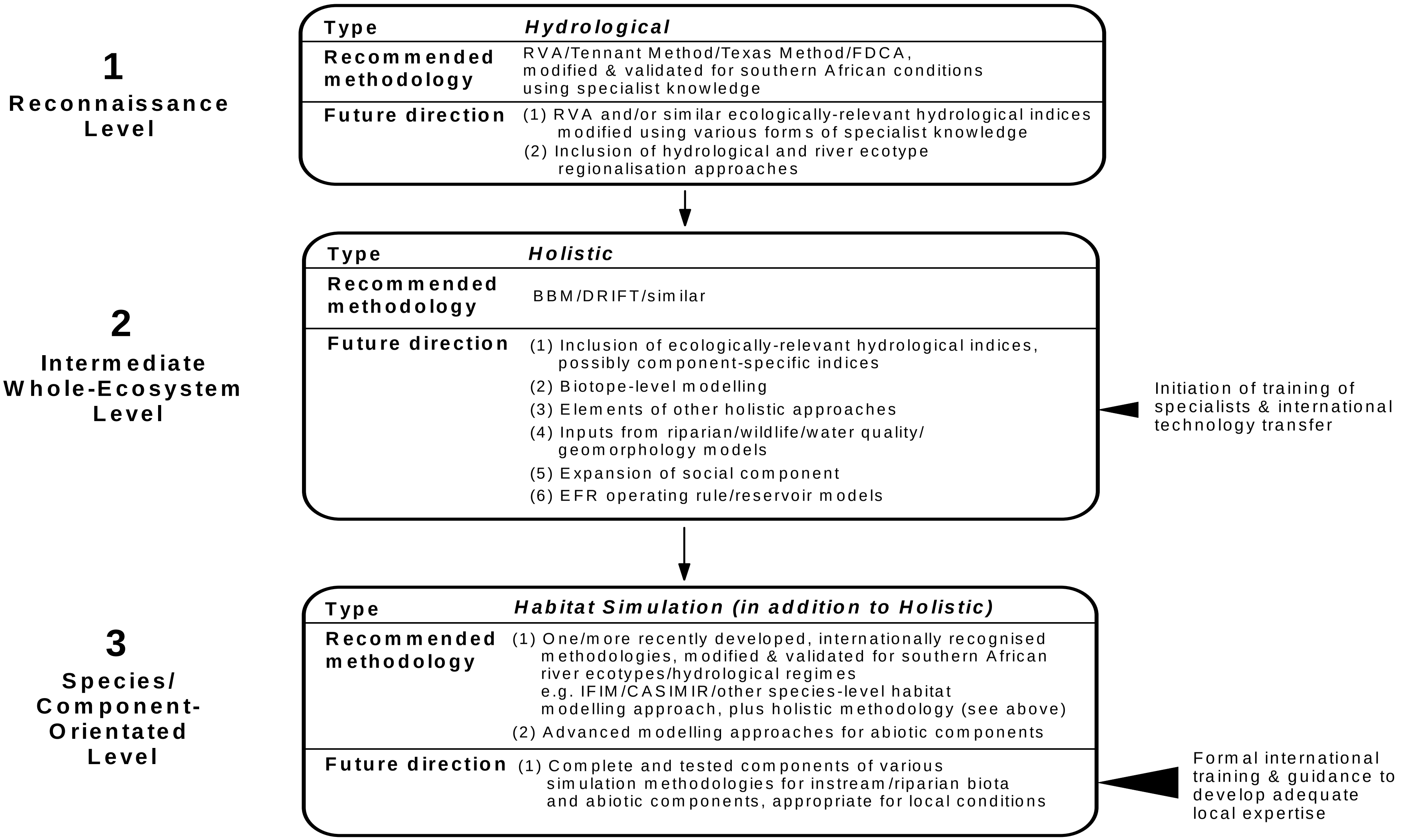

Figure 3.1 A hierarchy of environmental flow methodologies proposed for use in southern Africa (modified from Tharme 1997a).

4. ENVIRONMENTAL FLOW ASSESSMENTS WITHIN THE SOUTH AFRICAN INTEGRATED PLANNING PROCESS FOR WATER RESOURCES

Jay O'Keeffe

4.1 THE NEW SOUTH AFRICAN WATER LAW

In August 1998, a new Water Act was passed in South Africa (South African National Water Act No. 36 of 1998). A major innovation of the Act is the incorporation of the concept of the Reserve, which now represents the only water right within South Africa. The Reserve consists of two parts: the quantity and quality of water required for basic human use, and the ecological Reserve, which is defined as the quantity and quality of water required to protect the aquatic ecosystems which are the base of the water resource.

For the past decade, it has been the policy of the South African DWAF to assess the EFRs for river maintenance when a water-resource development is planned. The new Water Act gives legal status to this activity. A publication titled “Resource directed measures for protection of water resources” (DWAF 1999a) describes in detail how to set the Reserve. It lays out the policy and process to be followed for the determination of the ecological Reserve, and ultimately will describe the methods for both rapid and comprehensive determinations of flow requirements for different types of water bodies.

The purpose of this chapter is to explain the process of setting EFRs for rivers within the context of the new Water Act. In particular, the BBM is placed within the context of the process devised for setting the ecological Reserve. It is not intended here to provide a comprehensive description of how the Reserve is determined. Readers are referred to the above-mentioned document for that information.

4.2 THE ECOLOGICAL RESERVE WITHIN THE CONTEXT OF THE WATER RESOURCES PLANNING PROCESS

The DWAF has adopted the following sequence of phases for water-resource developments:

- Reconnaissance;
- Pre-feasibility;
- Feasibility;
- Design;
- Construction;
- Operation.

The duration of each phase depends on the size and scope of the project. Linked engineering and environmental activities (Table 4.1) as well as social activities occur in these phases. The different levels of assessment for the ecological Reserve (Desktop, Rapid, Intermediate and Comprehensive) are explained in Section 4.6. The BBM is the default methodology employed for the assessment of the quantity aspects of the Comprehensive ecological Reserve for rivers. It was designed to fit within the engineering phases, in terms of timing and resources required, so as to provide an integrated project planning process which consistently checks flow requirements for environmental maintenance with those of offstream users.

Table 4.1 The DWAF engineering and environmental phases for a water-resource development, showing positions of the environmental flow activities. The environmental activity shown in column 3 is elaborated upon in column 4. IEM - integrated environmental management.

ENGINEERING OR IEM PHASE	ENGINEERING ACTIVITY	ENVIRONMENTAL ACTIVITY	FLOW ACTIVITY
Phase 1 **Reconnaissance**	Catchment/systems analysis	Issues assessment; preliminary assessment of environmental flows (quality and quantity)	Desktop Estimate or Rapid Determination of the ecological Reserve; Habitat integrity assessment
Phase 2 **Pre-feasibility**	Possible development options identified	Impact assessment of each option; assessment of ecological Reserve	Intermediate Determination of the ecological Reserve; or Comprehensive Reserve assessment using the BBM or similar
Phase 3 **Feasibility**	Detailed investigation of selected option	Environmental impact assessment (EIA) completed	Refinement of ecological Reserve; Yield analysis; Catchment water budget; Scenario Meetings
Phase 4 **Design**	Engineering management plan	Environmental management plan	Baseline studies for monitoring programme
Phase 5 **Construction**	Implementation of engineering management plan	Implementation of environmental management plan	Baseline studies continue; Monitoring
Phase 6 **Operation**	Engineering audit	Environmental audit	Monitoring; Validation of ecological Reserve and adjustment if necessary

From the engineering perspective, a situation assessment takes place during the Reconnaissance phase, often in the form of a catchment (drainage basin) study or a regional systems analysis. This identifies several possible options for the development. At the same time an assessment is done of environmental issues of concern. At this stage a Desktop Estimate of the probable flow requirements for the study area may be made, along with a first estimate of offstream water requirements, in order to highlight development options where conflict between the EFR and potential offstream demand is likely to be high. An alternative to the Desktop Estimate is the Rapid Determination. Both are extrapolations of past estimates of EFRs for similar systems, but the Rapid Determination additionally involves limited field analysis (Section 4.6). Some proposed water-resource development options might be excluded at this stage.

The most probable of the remaining options from an engineering perspective are then investigated during the Pre-feasibility phase. This is paralleled by an EIA of each option, where some may be identified as environmentally unacceptable. This stage of the EIA usually also highlights the need to reduce potential impacts of any of the remaining options on the downstream river, by adherence to an agreed flow regime. At this stage the main assessment of this flow regime, the EFR or the quantity component of the ecological Reserve for rivers, should be undertaken, either at the Intermediate or Comprehensive level (see Section 4.6). In the Comprehensive process, the BBM or similar methodology may be used. The results will aid determination of whether or not the remaining options could deliver an environmentally acceptable flow regime and, if so, which option is preferred.

In the Feasibility and subsequent phases, those activities related to environmental and social issues (Louw 1995) are again matched with the engineering activities.

4.3 WHY IS AN ECOLOGICAL RESERVE NECESSARY?

Principle C3 of the South African Water Act of 1998 states: “The quantity, quality and reliability of water required to maintain the ecological functions on which humans depend should be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems”. DWAF’s (1994b) White Paper entitled “Water Supply and Sanitation Policy” adds that “The environment should not ... be regarded as a user of water in competition with other users, but as the base from which the resource is derived and without which no development is sustainable. Protection and conservation of the natural resource base is therefore imperative”. These are strong statements that support the need to protect natural resources, emphasising that this protection is to the advantage of humans.

The basic ecological concepts on which these principles are based are as follows.

- Water occurs within ecosystems, the components of which are interdependent. Thus, for instance, a riverine ecosystem encompasses, from source to sea, the surface and related underground water, the channel, instream biota, riparian plants and animals, transported sediment and natural chemicals, all of which are inextricably linked.
- Healthy aquatic ecosystems provide humans with a number of important ‘silent’ services, such as the retention, storage and consequent supply of water, and the dilution, removal and purification of wastes.

They also supply commercial and subsistence products such as fish and plants, and are important areas for recreation and tourism.

- These services have a finite capacity and may be over-used. The ecosystems providing them may then become stressed, with a consequent loss of the quality of the services over the long term. Such over-use is thus unsustainable.

4.4 STEPS FOR SETTING THE ECOLOGICAL RESERVE

A six-step process has been defined for determining the quantity aspect of the ecological Reserve for a section of river. This is summarised as a series of questions in Table 4.2, and expanded upon below.

Table 4.2 The six-step process that has become the backbone of the process for setting the ecological Reserve for rivers. Refer to Section 4.5 & Table 8.4 for definitions of habitat integrity classes.

QUESTION	RESERVE PROCESS	ACTION
1. What lengths of river constitute the study area?	Define geographical boundaries of the study area	Define the area (river lengths and tributaries) for which the Reserve is to be assessed.
2. Which parts of the rivers in the study area are similar?	Eco/geo-regional and water quality typing	Ecotyping and stream classification.
3. What were these river stretches like?	Reference Condition	Best estimate of natural hydrology, water quality, biota and channel form.
4. What are they like now?	Present Ecological State	Set classes A-F for habitat integrity, fish, invertebrates, vegetation, geomorphology, and water quality.
5. Classification **5.1: How ecologically important are the river stretches?** **5.2: In what condition should they be?**	Classification of the resource	Determine ecological and natural utilisation importance. Specialists + Stakeholders + DWAF define Ecological Management Class and objectives.
6. Assessing the ecological Reserve **6.1: What should be the future flow regime and water quality of the river(s)?** **6.2: What can practically be done to achieve this?**	Set the ecological Reserve	Set surface water requirements at specified sites. Model management scenarios taking account of all river uses. Assess ecological consequences.

Step 1: definition of study area

The extent of the study area, whether a whole river system, a main channel, or a channel section, is defined geographically.

Step 2: ecotyping

Since the whole length of the river cannot be sampled and assessed, the process for setting the Reserve is based on representative or critical sites. The location of the sites is crucial, and one should be located in each of the longitudinal river zones that are significantly different in terms of climate, geology, topography and vegetation type. The method by which this is done is ecotyping, which serves to identify the broad lengths of river within which each site should be located. Details of the ecotyping method can be found in Appendix R1 of DWAF (1999a).

Step 3: setting of Reference Condition

In order to set environmental objectives for the river, there must be some set of conditions against which to judge how much the system has been modified by human use. Usually equated to natural conditions, the Reference Condition represents the baseline against which the present condition of the system can be judged. The assessment is made either of an undisturbed part of the system or of a neighbouring system, or from historical records, and is used to represent the A class (undisturbed, natural) condition in the DWAF classification system (see Section 4.5, Table 8.4 & Chapter 11).

Step 4: present condition

The present condition of the river is classified for different components of the ecosystem (fish, invertebrates, riparian vegetation, water quality, geomorphology, social uses) and for the ecosystem as a whole. Details of the method used can be found in Appendix R6 of DWAF (1999a).

Step 5a: river importance

The ecological importance and sensitivity of the ecosystem are assessed in terms of, *inter alia*, its rare and sensitive species, habitat diversity and importance as a migration route. The method used is described in Appendix R7 of DWAF (1999a) and also in Chapter 10.

Step 5b: setting objectives

Setting of the ecological objectives and the EMC (see Section 4.5 & Chapter 11) is done in consultation with stakeholders and specialists. The ecological objectives may be to maintain the river in its present condition, or to improve some aspects. For instance, for the Letaba River, which flows into the Kruger National Park, one of the objectives was to reinstate perennial flow conditions. This was the natural flow regime, which was altered to non-perennial flow by irrigation abstractions that reduced flows in the 1950s and 1960s (Chutter & Heath 1993).

Step 6a: assessing the ecological Reserve (quantity)

A team of specialists applies the selected methodology (see Section 4.6), to describe a flow regime that should maintain the selected EMC.

Step 6b: yield analysis

The recommended environmental water volumes are incorporated in the yield model for the system, together with the user requirements (see Chapter 22). Water shortages and operational constraints are identified, and the specialists describe the ecological consequences of failure to provide any components of the EFR.

Following this process, the attainable environmental water requirements are agreed upon, together with plans on how to improve flow conditions to these recommended levels in the long term.

4.5 THE ECOLOGICAL MANAGEMENT CLASS

The process of setting the ecological Reserve centres on the concept that aquatic ecosystems may be maintained at different levels of condition (or ‘health’), from near-natural to severely modified (Chapter 2). As ecosystems are modified, their structure and functioning change, and valued features or ‘silent’ services may be lost or diminished. Valued features or services include:

- water storage;
- flood attenuation;
- water purification;
- recreational facilities (e.g. swimming, fishing, boating, hiking);
- conservation of wildlife;
- scenic beauty;
- food (e.g. fish);
- plants (e.g. for thatching, for medicine);
- stock watering;
- laundry facilities.

Following the process outlined in Table 4.2, identification of the desired condition is done using a system of river classification. This has been introduced by DWAF to help categorise the description of both present and desired river condition. Six classes of river condition or health, A-F, are recognised, with Class A being the least degraded condition and Class F the most degraded.

- Class A: close to natural condition.
- Class B: largely natural with few modifications.
- Class C: moderately modified.
- Class D: largely modified.
- Class E: seriously modified; no longer providing sustainable services.
- Class F: critically modified; no longer providing sustainable services.

The classes are used to describe the PES or present condition of the river (Appendix R6 of DWAF 1999a), and the EMC or desired future condition (Chapter 11). Any of the six classes may be used to describe the PES, but only Classes A-D to describe the EMC. This reflects the principle that severely degraded rivers should be rehabilitated in the long term.

The EMC is set for each section of a river, in procedures that take account of the technical assessments of the specialist river scientists and the wishes of the stakeholders. Under the new Water Act, however, the final decision on the EMC is the responsibility of the Minister of Water Affairs and Forestry.

The environmental flows described for maintenance of the chosen EMC may be assessed at several levels of resolution, depending on the position of the assessment in the planning process. This is explained further in the next section.

4.6 DIFFERENT LEVELS OF ECOLOGICAL RESERVE DETERMINATION

In order to provide a flexible response to different requirements for Reserve determinations, several levels of assessment have been developed. These are all based on the approach described above, but require different levels of resources, specialist input and time.

For a river with an abundance of unallocated water resources and no immediate plans for further development, the most simplistic method, the **Desktop Estimate**, might be sufficient. In a case where there are minor allocations and developments planned, an extended version of the Desktop Estimate, known as the **Rapid Determination** might be used. In cases where there is a possibility of conflict between the requirements of the Reserve and the users, an intermediate method known as the **Intermediate Determination** might be appropriate. In cases of major developments, or where the river is highly important and sensitive, a **Comprehensive Determination** using the BBM or similar would be required. The **Flow Management Plan** may be applied in rivers that have been highly and irreversibly regulated. Table 4.3 summarises the characteristics of the different levels of determination (see also Section 3.5). In general:

- greater detail results in higher costs, longer time required for the assessment, and higher confidence in the recommendations;
- faster, less detailed methods may, but by no means definitely do, result in more conservative Reserve recommendations;
- initial, less detailed estimates can be revised by moving to a higher level of assessment.

Table 4.3 Recommended methods for the assessment of the ecological Reserve (quantity), with indications of the resources required and type of results from each.

METHOD	RESOURCES REQUIRED	TIME REQUIRED	CONFIDENCE IN RESULTS	RESOLUTION OF RESULTS	RESERVE STATUS
Desktop	Low	2 days	Low	Low	Planning guide only
Rapid	Low	2 weeks	Low	Low	Preliminary Reserve
Intermediate	Medium	8 weeks	Medium	Medium	Preliminary Reserve
Flow Management Plan	High	32 weeks	Medium/High	Medium/High	Full Reserve
Comprehensive	High	32 weeks	Medium/High	Medium/High	Full Reserve

Other holistic methodologies exist that could be used for a Comprehensive assessment of the Reserve (Section 4.6.3), and these incorporate extensive data collection in the rivers in order to develop a quantitative predictive capacity of flow-related river changes. Data collection by a multidisciplinary team can take from one to five years, depending on how much is already known of the river, the extent of the water development and the social importance of the river. These methodologies produce high resolution results.

The following sections describe the main characteristics of each of the methods in Table 4.3. A decision tree (Figure 4.1) indicates which method should be used under different circumstances.

4.6.1 The Desktop Estimate and Rapid Determination

Described as a coarse desktop estimate of the ecological flow requirements for rivers for use in the **National Water Balance Model** (being undertaken by the Project Planning Directorate of DWAF), this method is based on available information. Within this model, the Desktop Estimate is a broadscale first attempt to quantify the amount of water that should be reserved as environmental flows in all of the quaternary catchments (there are 1946) in South Africa. The Desktop Estimate is intended for planning purposes only, and does not constitute a description of the ecological Reserve under the new Water Act. Where the results of a Desktop Estimate are challenged, as for instance by developers wishing to increase water abstraction beyond the limits indicated by the estimate, it is not intended that the Desktop Estimate should be defended. Instead, a more detailed assessment method should be implemented to refine and increase confidence in the description of the recommended flows.

The Desktop Estimate:

- is based on quaternary catchments using WR90 simulations of runoff (Midgely *et al.*, 1994a);
- is based on a default PES and EMC;
- provides an estimate for water quantity only, through a Decision Support System (DSS) Model that extrapolates from the results of past EFAs in South Africa (Hughes *et al.*, 1997).

An extended version of the Desktop Estimate, known as the Rapid Determination, uses the same methods, but employs a preliminary assessment of habitat integrity (Appendix R4 of DWAF 1999a).

4.6.2 The Intermediate Determination

The Intermediate Determination was developed specifically to provide an assessment of the ecological Reserve within a time period of 60 days, which is the time within which DWAF should decide on issue of a water licence. Without this facility, the process of setting the Reserve might delay the issuing of licences, resulting in a backlog of licence applications and unacceptable delays for urgent water-resource development projects. It is intended for use as a rapid response in cases of small-scale water developments, on rivers of medium or low ecological importance. As with the Desktop Estimate and Rapid Determination, where its results are in dispute a more detailed method should be implemented to refine the assessment and increase confidence.

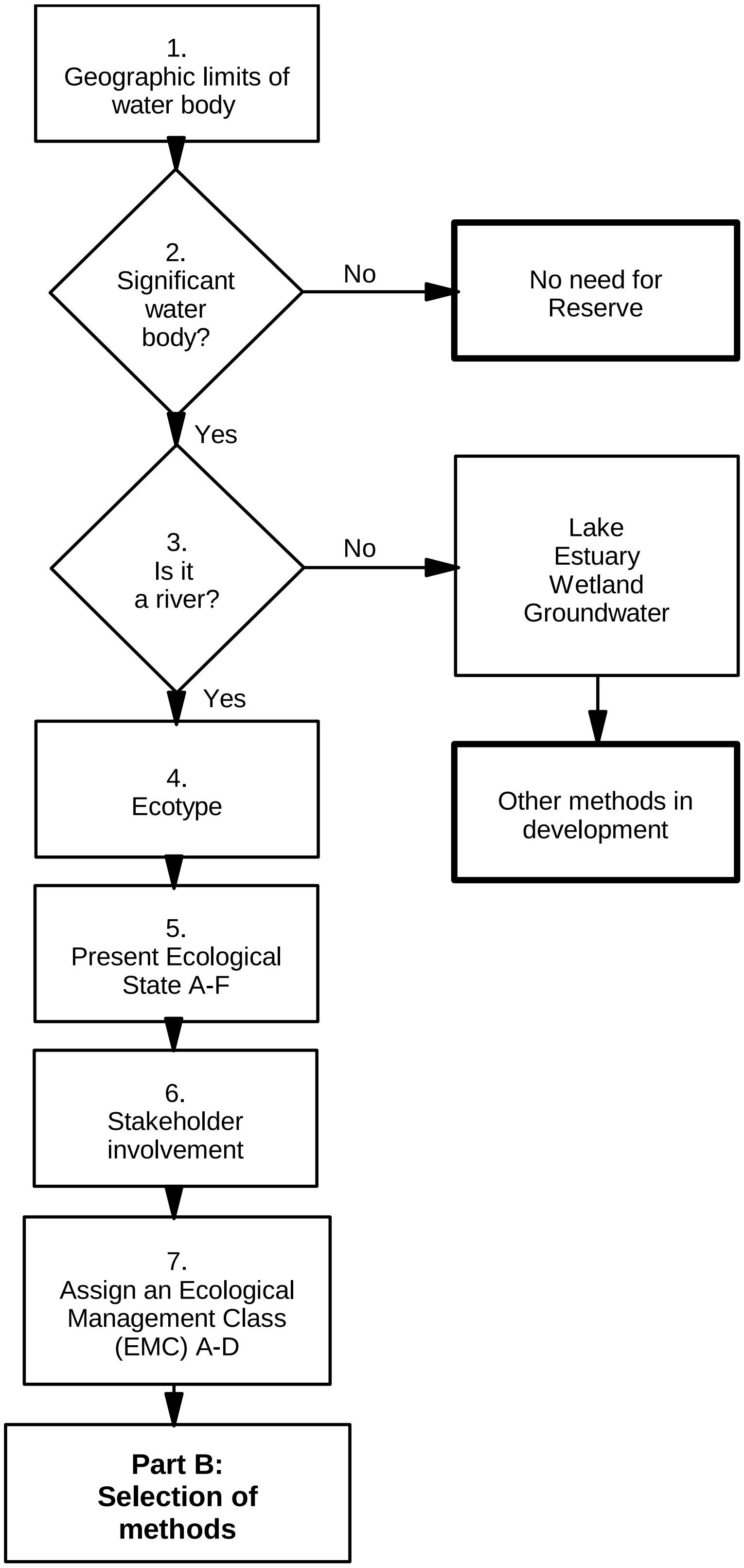

Figure 4.1 **A decision tree demonstrating the different routes to be followed for the assessment of the ecological Reserve in response to different types of rivers and proposed water-resource developments. Part A: Preliminary classification.**

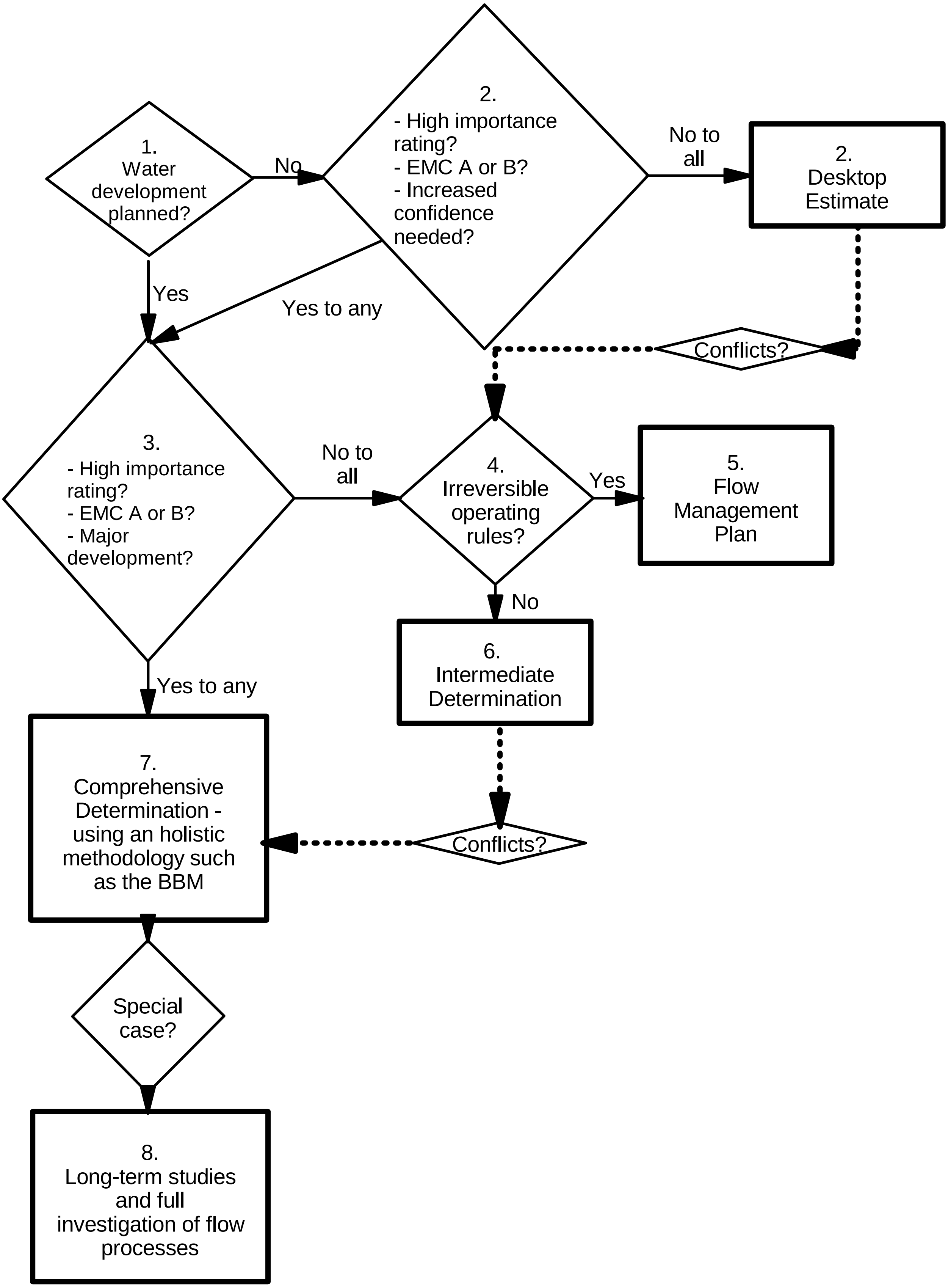

Figure 4.1 **Continued. Part B: Selection of methods. Note: the dotted lines indicate that there is always the potential to upgrade preliminary assessments by more detailed studies. In terms of the Water Act, preliminary estimates must be reviewed and upgraded within a given period.**

The characteristics of the Intermediate Determination are that it should:

- be determined in a period of not more than 60 days;
- follow the conceptual principles of the BBM (Chapter 5);
- involve less detailed preparatory work than the BBM;
- be applied by a small group of specialists in a field assessment of the flow requirements.

The method does not require consultation with stakeholders, but an optional socioeconomic assessment may be made, using available information.

4.6.3 The Comprehensive Determination

The Comprehensive Determination is designed to provide medium confidence assessments of the ecological Reserve within the timeframe for planning water-resource developments. The BBM was the first holistic methodology developed in South Africa for assessment of the EFRs for rivers (Section 3.5), and has thus evolved with the new Water Law to become the core methodology for determining the quantity component of the ecological Reserve for rivers. Other holistic methodologies appropriate for use in South Africa have since been developed in southern Africa (DRIFT; Section 3.5) and Australia (FLOWRESM; Section 3.5). These have alternative or additional features to the BBM, and could equally well be used for setting environmental flows.

The comprehensive flow assessment is normally carried out during the Pre-feasibility study phase, which may last for eight months to more than a year for a medium-sized project. Use of the BBM to make the assessment is described in this manual.

4.6.4 The Flow Management Plan

A specialised version of the Comprehensive Determination, the FMP (Section 3.5), is used for recommending flow modifications for systems that are already considerably modified, and for which there is no realistic possibility of their being returned to any semblance of their natural conditions. Present irreversible changes to the river are acknowledged, and possible flow modifications which could aid rehabilitation of the river, without unacceptably prejudicing the present operation of the system, are recommended. The approach, timing and resources used are similar to those for the Comprehensive Determination.

5. OVERVIEW OF THE BUILDING BLOCK METHODOLOGY

Jackie King

5.1 ORIGIN OF THE BUILDING BLOCK METHODOLOGY

The BBM originated in two major South African specialist workshops on EFAs, where parts of it began evolving in the form of the “Cape Town” and “Skukuza” approaches (King & O’Keeffe 1989; Bruwer 1991). Parallel development by Australian colleagues led to a joint description of an approach (Arthington *et al.*, 1992), at that time termed the “Holistic Method” in Australia and now expanded to a more encompassing Holistic Approach (Section 3.5). Further separate developments took place in South Africa during applications of the methodology, which were recognised through the final South African name of the BBM. These workshop applications, each designed to produce a relatively rapid, first estimate of the EFR for a river targeted for water-resource development, were mostly convened by the Environment Studies sub-directorate of DWAF (Tharme & King 1998), and involved many of the country’s most experienced river scientists.

Between 1991 and 1996, BBM workshops were held for the following rivers: in South Africa the Lephalala, Berg, Olifants (Western Cape), Olifants (Transvaal), Letaba, Luvuvhu, Lomati, Koekedouw, Mooi, Tugela, Mvoti, Sabie, and Bivane; in Lesotho the Senqu River; and in Australia the Logan River. Although more BBM applications have taken place since, these early ones produced the essential nature of the approach to flow assessments encompassed in the BBM. Documents of the information prepared for, and the proceedings of, all these workshops except that for the Logan, can be obtained from DWAF. Documents for the Logan River workshop can be obtained from A. Arthington, Centre for Catchment and In-Stream Research, Griffith University, Nathan, Queensland, Australia.

5.2 ASSUMPTIONS AND CHARACTER OF THE BUILDING BLOCK METHODOLOGY

In the methodology the following assumptions are made.

- The biota associated with a river can cope with those low flow conditions that naturally occur in it often, and may be reliant on higher flow conditions that naturally occur in it at certain times. This assumption reflects the thinking that the flows that are a normal characteristic of a specific river, no matter how extreme, variable or unpredictable they may be, are ones to which the riverine species characteristic of that river are adapted and on which they may be reliant. On the other hand, flows that are not characteristic of that river will constitute an atypical disturbance to the riverine ecosystem and could fundamentally change its character.
- Identification of what are felt to be the most important components of the natural flow regime and their incorporation as part of the modified flow regime will facilitate maintenance of the natural biota and natural functioning of the river.
- Certain kinds of flow influence channel geomorphology more than others do. Identification of such flows and their incorporation into the modified flow regime will aid maintenance of the natural channel structure and diversity of physical biotopes.

In total, the flows incorporated into the modified flow regime will constitute the EFR for the river. As the minimum acceptable value will have been entered for each flow component incorporated, the EFR describes, in space and time, the minimum amount of water that it is felt will facilitate maintenance of the river at some predefined desired state (i.e. the identified EMC; Section 4.4).

The recommended flows are identified and their magnitudes, timing and duration decided upon in a BBM Workshop (see Chapter 21). Initially, thought is focused on the characteristic features of the natural flow regime of the river. The most important of these are usually: degree of perenniality; magnitude of baseflows in the dry and wet season; magnitude, timing and duration of floods in the wet season; and small pulses of higher flow, or freshes, that occur in the drier months (Figure 5.1). Attention is then given to which flow features are considered most important for maintaining or achieving the desired future condition of the river, and thus should not be eradicated during development of the river's water resources (Figure 5.1). The described parts of each flow component are considered the building blocks that create the EFR, each being included because it is understood to perform a required ecological or geomorphological function (Figure 5.2). The first building block, or low flow (baseflow) component, defines the required perenniality or non-perenniality of the river, as well as the timing of wet and dry seasons. Subsequent building blocks add essential higher flows.

5.3 SEQUENCE OF ACTIVITIES IN THE BUILDING BLOCK METHODOLOGY

The BBM has three main parts, which encompass preparations for and running of the BBM Workshop, and follow-up activities that link the workshop with the engineering and planning concerns.

5.3.1 Part one of the Building Block Methodology - preparation for the workshop

A structured set of activities is followed to collect and display the best available information on the river, for consideration by the workshop participants. Coordination of the activities takes place early in the process through a BBM Planning Meeting and follow up activities (Chapter 6). The topics dealt with, each by a senior specialist in the field, are explained in Chapters 8-19. In summary, the main sequence of pre-workshop specialist activities is outlined below (see also Chapter 20).

Appointment of a study coordinator

The first task of the coordinator is an assessment of the nature of the targeted river, the proposed water-resource development, the literature available on the river and likely key issues. The findings guide the extent of the next activity, in terms of the length of river system to be surveyed during a low-level flight (Chapters 6-8). They also guide selection of an appropriate team of specialists for the study.

Determination of the present habitat integrity of the area likely to be affected by the development

(What is the present condition of the river, in terms of available instream and riparian habitat for riverine plants and animals?) A low-altitude aerial survey along the river by helicopter is completed during low flow conditions. A video film taken during the flight is used to separately analyse instream and riparian habitat integrity. Results are given per 5 km stretch of river. The method is described by Kleynhans (1996), and in Chapter 8. The video is also analysed by a fluvial geomorphologist in a reach analysis (Section 14.3.2), whereby similar stretches of channel are identified and described. Both sets of results are used at the Planning Meeting to provide an understanding of the nature of the river and its present condition, and to aid identification of representative reaches and sites along the river that will become the focus of the BBM activities.

Holding of the Planning Meeting

During this meeting, the study area is formally delineated, the results of the video survey are considered, present relevant knowledge on the river is assessed, and representative reaches and sites are tentatively identified (Chapter 6). (Which stretches of the river would be directly affected by flow manipulations from the proposed development and thus should be dealt with in the workshop? Which reaches and sites in combination could represent the river within the study area? What do we presently know about the nature of the river ecosystem in the study area?) The specialist team meets for the first time, and should include, as a minimum: an hydrologist; hydraulic modeller; fluvial geomorphologist; aquatic chemist; ecologists specialising in studies of fish, aquatic invertebrates and instream and riparian vegetation; and a social consultant. If appropriate, additional specialists could include a geohydrologist; a geochemist; an ornithologist; and experts dealing with riverine mammals, herpetofauna and terrestrial, water-dependent wildlife. The habitat integrity specialist reports on the videographic survey, and the fluvial geomorphologist on the reach analysis. Following assessment of this and other present knowledge, such as that of the distribution of plant and animal species in the river, additional data needs for applying the BBM are identified. The potential representative reaches and sites are chosen (Chapter 7).

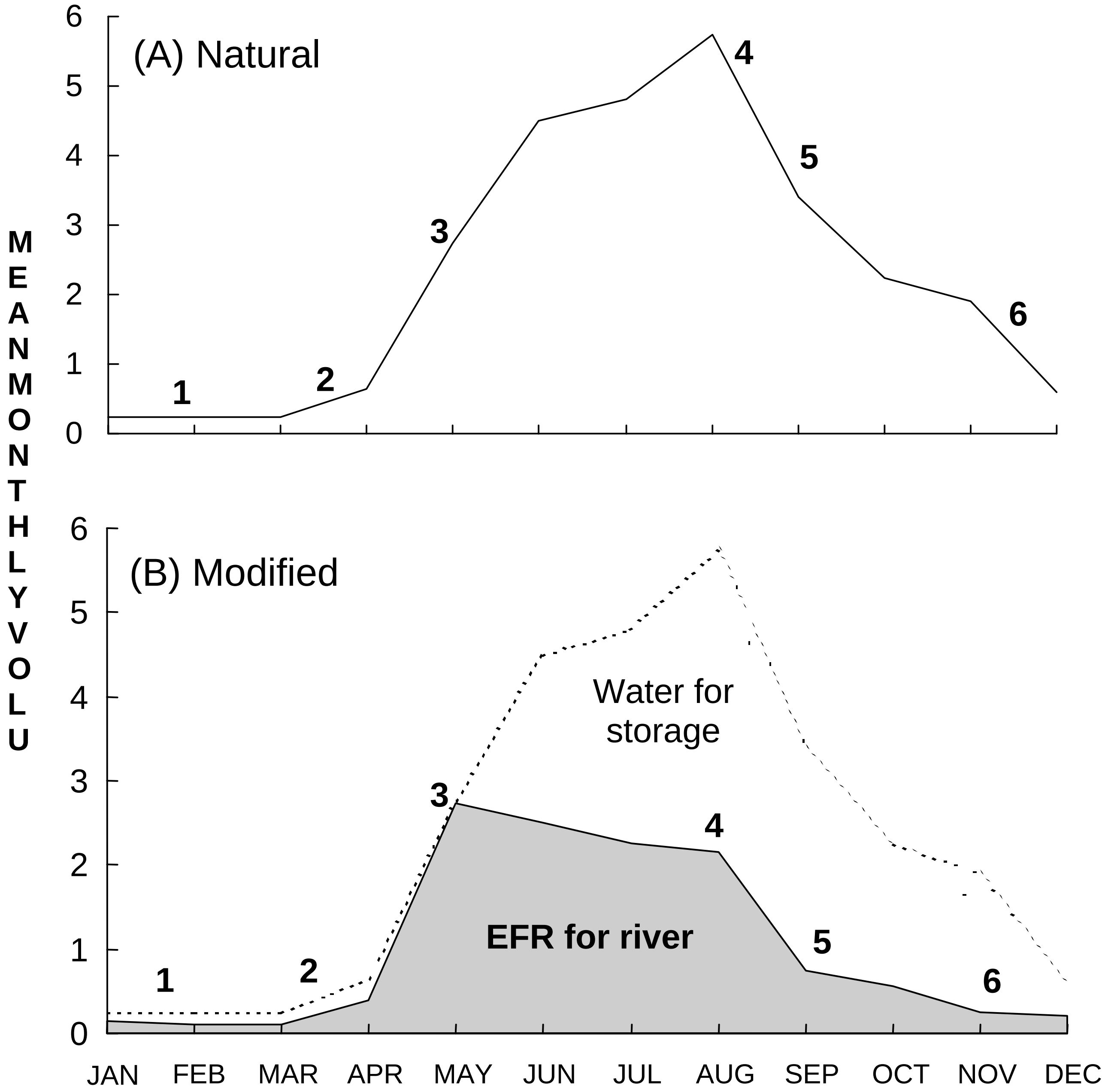

Figure 5.1 Focusing thought on (A) perceived important features of a river's natural flow regime and (B) which of these should be retained in an EFR (modified from Tharme & King 1998). For instance, features 1 and 6 may recognise the perenniality of the river (A) and the need to retain this (B); features 2, 4 and 5 may recognise the need to retain the fundamental difference between wet season and dry season baseflows; and feature 3 may recognise the timing of the first major flood of the wet season and the need to retain this.

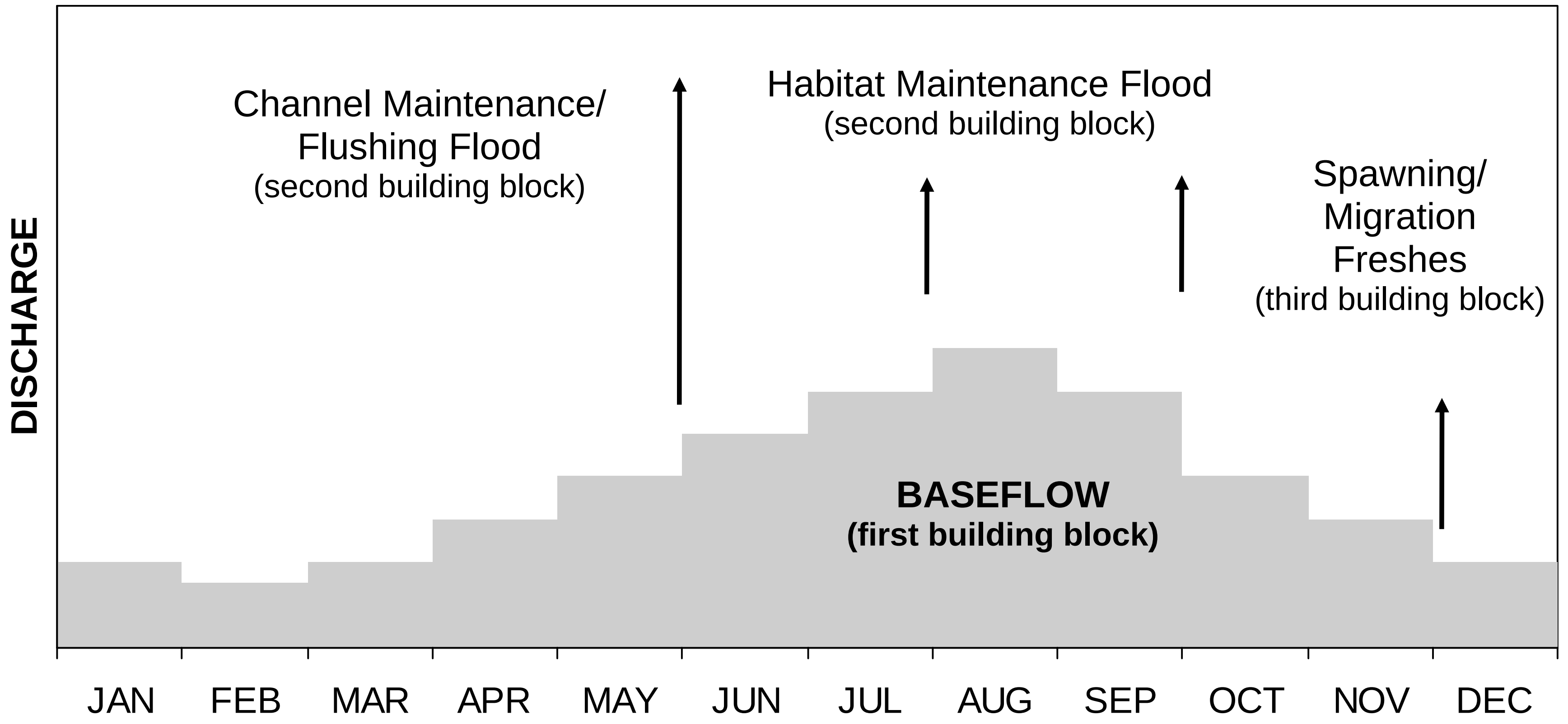

Figure 5.2 An hypothetical EFR created using the BBM (from Tharme & King 1998).

Identification of representative reaches and sites within the study area

These BBM sites will form the focus for most of the collection or creation and analyses of new data required specifically for the workshop. (Knowing to some extent the biological, chemical, hydrological and geomorphological longitudinal zonation and other special attributes of sections of the river, which reaches need an individual assessment of their EFR? Which sites within the reaches will be used for those assessments?) This activity is initiated in the Planning Meeting, and completed in the field visit directly afterwards. Each chosen site will have an EFR described for it. At a minimum, the fish, riparian and invertebrate ecologists, the geomorphologist, the hydraulic modeller, the survey team and the BBM specialist should be involved in the selection of the sites and of the representative cross-sections at the sites (Chapter 7).

Completion of a social survey of the study area

(Are there rural communities, or any other group(s) of people, directly dependent on the riverine ecosystem for their subsistence in terms of food, potable water, medicines, building material, grazing, or cultural and religious activities?) (Chapter 9). Early knowledge of this nature, gleaned during the initial appraisal, feeds into determination of the EMC (see below & Chapter 11).

Determination of the importance of the study area

The ecological importance of the study area at the local, regional, national and international level is determined. (How important is the river economically, socially and ecologically?) The assessment is based primarily on existing information and expert knowledge (Chapter 10). Expansion of the approach to include social and economic components is at an early stage.

Determination of the Ecological Management Class for the river in the study area

(In what environmental condition should the river be maintained, in the future?) Determination of the EMC (Chapter 11) takes place through informal discussion with the social consultant, and a range of relevant institutions, including DWAF, the Department of Environment Affairs and Tourism (DEAT), and the Provincial Nature Conservation body. The objective is to identify a realistic EMC, which could be closer to or further from the river's pristine state than at present, or about the same. Updated knowledge on all the above topics is taken into consideration, as well as general catchment concerns about the condition of the river, and present and possible future land-use (Chapter 4). This EMC guides deliberations at the BBM Workshop, where the modified flow regime described is designed to aid its achievement and maintenance. More intensive public participation regarding the desired EMC occurs later at the scenario stage, in the light of the results of the hydrological yield analyses (see Chapter 22).

Description of the virgin and present daily flow regime

(What are the essential natural and present characteristics of the various BBM flow components at the selected sites?) Where necessary, these flow regimes are simulated for the selected sites along the river. This is the first of the specialist studies that focuses on the chosen BBM sites (Chapter 12). The hydrological data are an input to the flow deliberations that take place at the workshop, and the ensuing flow recommendations are cross-checked with the data to ensure realistic flows are being described.

Surveying and hydraulic analysis of channel cross-sections at each site

Consequently, through an hydraulic model, there can be development of stage-discharge relationships and other data on discharge-related links between hydraulics, channel morphology and biotopes. (What is the shape of the channel at each site, how do hydraulic conditions change with discharge and where does the water lie in the channel at those discharges? What physical biotopes are present and how are these likely to be affected by changes in discharge?) (See Chapter 13).

Assessment of the geomorphological characteristics of the study area

(Which reaches of the study area are different in terms of geology, channel shape, substrata and diversity of physical biotopes?) Maps of catchment geology, topography, sediment production, land use, precipitation and runoff are used to identify likely linkages between the catchment and the changing character of the river. The results are combined with information gleaned from the helicopter survey and any aerial photos, to produce a description of the present geomorphological nature of the river, and identification of sensitive areas likely to change with future flow manipulation. The method is described by Rowntree & Wadeson (1998) and in Chapter 14.

Assessment of the past, present and required future water chemistry of the study area

(Bearing in mind the EMC for the river, from an ecosystem perspective and from that of humans directly dependent on the river, what chemical criteria should be adhered to in future?) This component was not well developed in the original programme of development of the BBM, as the accent was on quantity, not quality, aspects. However, it is recognised that the EFR cannot be effective in terms of the EMC unless water quality conditions are also suitable, and current research is aimed at enhancing this component (Chapter 15). Dilution flows to solve water quality problems are not seen as environmental flows, but may be superimposed on the EFR.

Completion of biological surveys at selected points throughout the study area, and of literature surveys

This allows updating of knowledge of species distributions and the determination of longitudinal zonation of the river. Additionally, physical and chemical tolerance ranges, specific flow-related requirements, and vulnerable lifecycle stages, of key species are ascertained to the extent possible within the study time. (Which reaches of the study area are different in terms of the biota, and what is the characteristic biota of each? Are there any sites, species or communities of special importance? What are the key species in the system and their essential flow-related requirements?) Ecosystem components always reported on are the riparian vegetation communities, the aquatic invertebrates and the fish (Chapters 16-18). Inputs on aquatic mammals, reptiles and amphibians, water birds and macrophytes can be included if available. Thus, the methodology can incorporate and use any relevant information on the river.

For ephemeral, sand bed rivers, analysis of groundwater hydrology at each site

(What is the depth of the water table during times of no surface flow? How does this affect the river plant and animal communities?) The information is also used to assess the use and availability of water holes in the riverbed for rural communities, stock or wildlife and may be linked to root depth of riparian trees (Chapter 19).

Part one of the BBM culminates with production of a document for the workshop, the starter document, which contains background information on the proposed water project and a chapter by each specialist (Chapter 20).

5.3.2 Part two of the Building Block Methodology - the workshop

Each BBM Workshop involves the water managers, engineers and river scientists involved in part one of the methodology. A chairperson and facilitators experienced in the BBM guide participants to consensus on an EFR for the river. The workshop (Chapter 21) consists of four main sessions.

Session 1: a visit to each site by the full team

On site, each specialist describes the river from his/her perspective. Cross-section and stage-discharge data are provided and discussed, and each participant completes a questionnaire on each site to aid later discussions. The discharge at the time of the visit is given.

Session 2: the exchange of information

Short presentations are given of each specialist report in the documents for the workshop. Participants are expected to be familiar with all the material presented, and the session is used to clarify uncertainties through questions. The Habitat Integrity specialist shows an edited video of the aerial survey of the river.

Session 3: compilation of the Environmental Flow Requirement

Participants are allocated to groups, each containing at least one specialist from each of the relevant sciences and facilitated by a river scientist experienced in the BBM. The BBM sites are allocated to the groups, and each group then focuses on the EFR, one site at a time.

Identification and description of the EFR for each site is done in a specific way (Chapter 21). After general discussion of the kind of flow regime that would facilitate maintenance of the EMC (Chapter 11), required flows are identified month by month, starting with the low flows. For each month, each river specialist except the hydrologist and hydraulic modeller is asked to describe the low flow needed from his or her perspective, stating its significance as knowledge and data allow. Required higher flows are then described in a similar fashion.

Throughout the process, the hydraulic modeller interprets the implications of flows described, in terms of depth, wetted perimeter, velocity, or areas inundated, using the surveyed cross-sections and plots of the various hydraulic relationships (Figure 5.3). These cross-sectional profiles and associated hydraulic plots are the vital communication link between ecologists and engineers, allowing intuitive or formal knowledge on species' flow requirements to be converted to discharge values of use to the planner.

The details of the flows identified are added one by one to a blank EFR table of discharge (rows) versus calendar months (columns) (Table 5.1). Each addition is described in terms of four criteria: magnitude, timing, frequency and duration, with relevant motivation being supplied by each contributing specialist. Floods up to those with a three-year return period are described, and the continued occurrence of larger ones is checked separately during the whole-catchment analysis in the Feasibility phase (see Chapter 22). Usually, each entry remains within the limits of the natural hydrograph, with the EFR thus being a skeleton of the natural flow regime. Each entry is also identified as a volume of water and a percentile on its calendar month's FDC. This allows biologists and others to understand the implication of flows they have asked for in terms commonly used by engineers. Finally, the low flow and high flow components of the EFR are expressed as percentages of the MAR and median annual runoff.

As consensus is reached on the EFR for a BBM site, the flows requested are compared to the natural hydrograph for the site, as a check that realistic figures have been produced. Flows are also recommended that will stress the river ecosystem in drought years (EFR for drought - Table 5.1), for such stress and variability in flow is felt to be an essential, natural feature of the country's rivers. Capping low flows may also be identified, to guide on upper limits for high volume dam releases down the river. Plenary report-back sessions are convened when appropriate.

Session 4: the final session of the workshop

The final session contains five main activities spread over about half a day. The recommended flow regimes for all the EFR sites are compared, to check that there are no major mismatches in what is proposed. Statements are made regarding the environmental acceptability of the options considered in the workshop. Further necessary work is identified and usually falls into three categories: short-term research required to address serious uncertainties, so that the EFR can be refined if necessary; medium-term research required to improve the BBM; and long-term fundamental research on subjects about which little is known. A *post mortem* of activities also takes place at the workshop, and any other statements that participants wish to make are noted and discussed if necessary. Reports on all these activities form part of the workshop report (Chapter 21).

5.3.3 Part three of the Building Block Methodology - linking environmental and engineering concerns

Part three occurs after the BBM Workshop, linking in at the end of DWAF's Pre-feasibility phase (Chapter 22). Outside of the BBM, the flow regime described in the workshop is incorporated in an hydrological yield analysis. This reveals whether or not the EFR can be met without conflict with potential offstream users. Where conflict is likely, scenarios can be created by the BBM team of possible consequences for the functioning of the river of flows that do not meet the EFR. The process is aided by a new hydrological model, the IFR Model, designed to transform the single numbers of the EFR table into a daily hydrograph, through linkage to current catchment climate (Hughes *et al.,* 1997). This, in turn, can be linked to national water resource models, through development of a conceptual EFR algorithm (Chapter 22).

Additionally, the scope of the study broadens from an EFA for the study area, to a coarse flow-related assessment of the implications for the complete river system. Findings from all these activities are combined to produce for the public descriptions of the EMC, with its flow requirement. Two or three other possible EMCs, which would require less or more water than the first EMC, are also described. Each EMC is also linked to its probable social and economic consequences, such as changes in the amount of irrigable land and the cost of water (Chapter 22).

These different EMC scenarios are used in meetings linked to the public participation process, in a way presently under development. The process ends with a decision by DWAF on water allocations, which reveals whether or not the project will proceed and the EFR will be met. If the project proceeds with agreement to meet the EFR, key participants of the workshop make input to scheme design, and the planners use the EFR figures to reserve water for the river during the planning process.

During late Feasibility or Design phases, baseline studies should take place, to record, in greater detail than is usually possible for the BBM Workshop, pre-development conditions in the river. These studies will aid design of a monitoring programme, which will be used to assess adherence to the agreed EMC for the river. Adjustments to the EFR could then take place based on the monitoring results (Chapter 22).

If a decision is taken not to meet part or all of the EFR, the BBM specialists would be able to advise on the least damaging way of managing the remaining flows in the river and, again, design an appropriate monitoring programme.

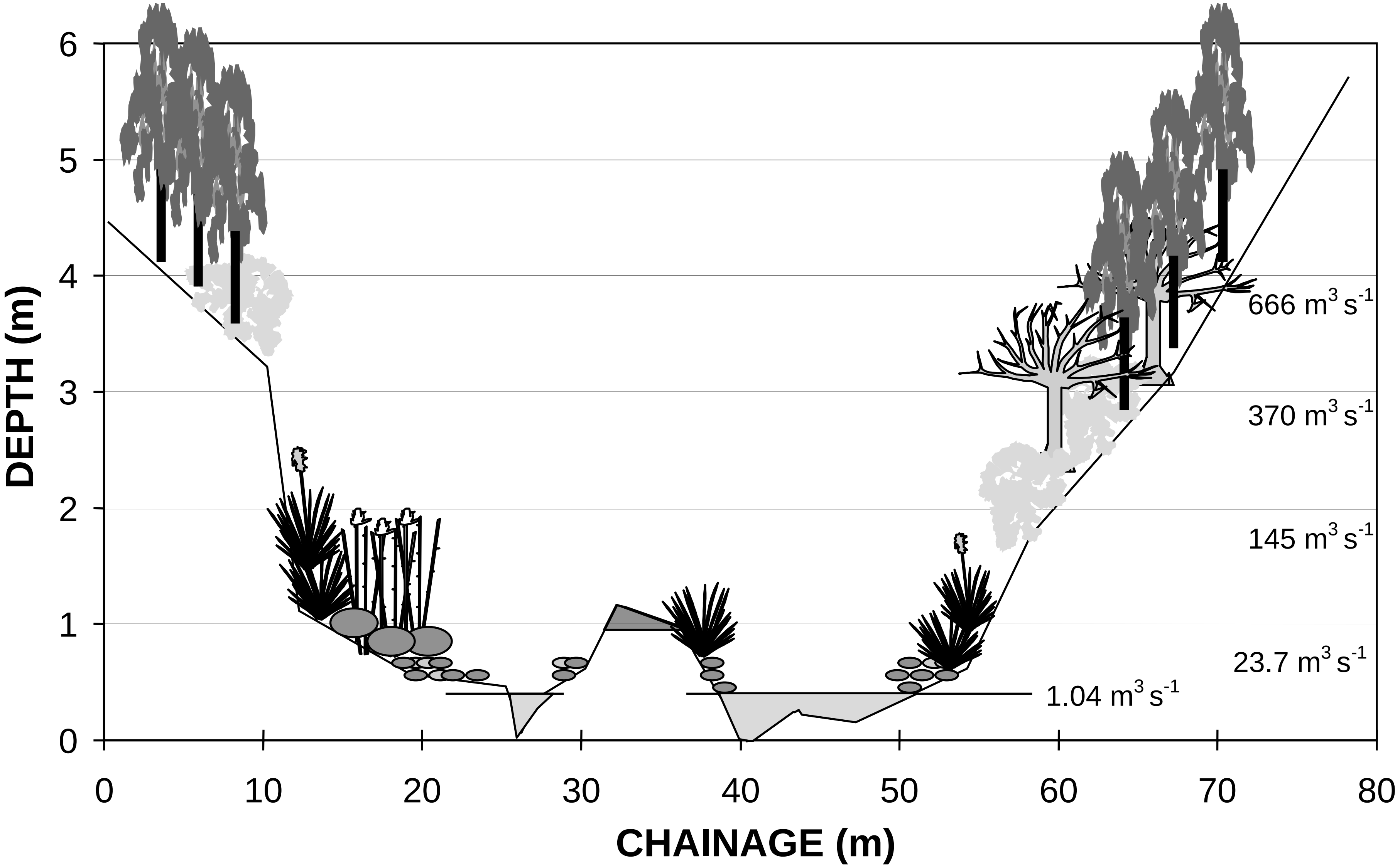

Figure 5.3 Example of a cross-section used in a BBM Workshop to link ecological knowledge to discharges (from King & Louw 1998).

Table 5.1 An example of an EFR table, for BBM site 1 on the Marite River (from Tharme 1997c). FDC - flow duration curve; MCM - million cubic metres; MAR - mean annual runoff; V - virgin; P - present day.

BUILDING BLOCKS		OCT	NOV		DEC		JAN			FEB			MAR	APR	MAY	JUN	JUL	AUG	SEP
MAINTENANCE EFR BASEFLOWS	**Magnitude ($m^3 s^{-1}$)**	0.9	1.1		1.9		2.1			3.0			2.5	2.0	1.5	1.3	1.1	1.0	0.8
	Depth (m)	0.36	0.39		0.47		0.49			0.55			0.52	0.48	0.43	0.41	0.39	0.38	0.35
	Volume (MCM)	2.4	2.8		5.1		5.6			7.3			6.7	5.2	4.0	3.4	2.9	2.7	2.1
	FDC % V	95	95		92		95			83			89	94	95	95	95	95	97
	FDC % P	69	80		77		76			72			80	84	88	79	78	75	78
HIGHER FLOWS	**Magnitude ($m^3 s^{-1}$)**		3.0	8.0	5.0	20.0	4.0	5.0 (X 2)	8.0	4.0 (X 2)	5.0	25.0 / 50.0	3.5 (X 2)						
	Depth (m)		0.55	0.80	0.67	1.17	0.61	0.67 (X 2)	0.80	0.61 (X 2)	0.67	1.29 / 1.84	0.59 (X 2)						
	Duration (d)		2	2	2	3	2	2 (X 2)	2	2 (X 2)	2	6 / 6	2 (X 2)						
	Return Period (y)		1:1	1:1	1:1	1:1	1:1	1:1 (X 2)	1:1	1:1 (X 2)	1:1	1:1 / 1:3	1:1 (X 2)						
	Volume (MCM)		0.2	0.6	0.3	2.4	0.2	0.3 (X 2)	0.5	0.1 (X 2)	0.2	5.7 / 12.2	0.1 (X 2)						
	FDC % V		43	8	40	3	59	48 (X 2)	31	72 (X 2)	66	2 / 1	79 (X 2)						
	FDC % P		21	5	28	2	45	38 (X 2)	25	64 (X 2)	59	11 / 5	67 (X 2)						
CAPPING FLOWS		No unseasonal pulses																	
DROUGHT EFR BASEFLOWS	**Magnitude ($m^3 s^{-1}$)**	0.2	0.5		0.8		1.0			1.0			1.0	0.8	0.5	0.2	0.2	0.2	0.2
	Depth (m)	0.21	0.30		0.34		0.38			0.38			0.38	0.34	0.30	0.21	0.21	0.21	0.21
	Volume (MCM)	0.5	1.3		2.1		2.7			2.4			2.7	2.1	1.3	0.5	0.5	0.5	0.5
	FDC % V	100	100		99		97			97			97	99	100	100	100	100	100
	FDC % P	100	97		96		99			100			100	100	100	100	100	100	100
HIGHER FLOWS	**Magnitude ($m^3 s^{-1}$)**		5.0				8.0						5.0						
	Depth (m)		0.67				0.80						0.67						
	Duration (d)		2				2						2						
	Return Period (y)		1:1				1:1						1:1						
	Volume (MCM)		0.4				0.6						0.4						
	FDC % V		15				31						64						
	FDC % P		10				24						53						

MAINTENANCE EFR	BASEFLOW	HIGHER FLOWS	TOTAL	**DROUGHT EFR**	BASEFLOW	HIGHER FLOWS	TOTAL
VOLUME (MCM)	50.2	13.3	63.5	VOLUME (MCM)	17.1	1.4	18.5
AS % OF MAR	(V) 29.5 (P) 36.1	(V) 7.8 (P) 9.6	(V) 37.3 (P) 45.7	AS % OF MAR	(V) 10.1 (P) 12.3	(V) 0.8 (P) 1.0	(V) 10.9 (P) 13.3
MAR (MCM)	(V) 170	(P) 139					
MEDIAN ANNUAL RUNOFF (MCM)	(V) 143	(P) 112					

6. INITIATION OF THE BUILDING BLOCK METHODOLOGY STUDY

Delana Louw

6.1 INTRODUCTION

The BBM is an overarching methodological framework for collecting and managing data on rivers in order to advise on management of their flows. Individual specialists from many disciplines are involved in the process (Section 5.3), requiring a high level of informed team coordination and management. This chapter describes the activities and information required to initiate a study in which the BBM is applied. Associated time and costs are not provided as this is dependent on the complexity of the study, and the size of the study area.

6.2 INITIATION OF THE STUDY

The study is initiated by the client, who approaches a coordinator familiar with the BBM and with riverine ecosystem functioning to act as the consultant. Writing of a proposal requires the design of a custom built approach within the framework of the BBM that is appropriate for the river of concern, and an associated budget. The coordinator's first task is to complete an overview assessment of what is known about the targeted river. Particular aspects that should be addressed include:

- the likely position(s) of the proposed water-resource development and thus the likely extent of the BBM study area (Section 6.3);
- present utilisation of the water resource, and how this is impacting the aquatic ecosystem;
- the likely extent and severity of impacts that could be caused by the proposed water-resource development;
- a broad categorisation of river type;

- existing ecological and environmental information on the system, and implications for the extent of studies required within the BBM;
- identification of the disciplines that should be represented in the ensuing BBM study, suggestions of suitable specialists and formulation of the team for the assessment using the BBM.

On acceptance of the proposal, the BBM team uses the above as introductory information. Terms of Reference are provided for each specialist.

6.3 PRELIMINARY DELINEATION OF THE STUDY AREA

The first step in preparing for the BBM study is delineation of the study area. This is needed to ensure that the study is confined to an area that is relevant in terms of the possible impacts of the water-resource development, and that it adequately represents all potential areas of concern within the river system.

Environmental flow assessments may be undertaken in response to a proposed water-resource development, or simply to set baseline flow requirements for a river, perhaps for purposes of regional planning. In most cases, the BBM is applied in the former case, to ascertain an EFR for a river stretch that would be impacted by a proposed development. In this case, the upstream limit of the study area is defined as a point upstream of any impact of the proposed development. The downstream limit of the study area may be based on a number of considerations, including one or more of the following criteria:

- the length of river, and thus the number of sites, that could be catered for in a four-day BBM Workshop;
- the downstream extent of the freshwater part of the river (i.e. to the upstream end of the estuary);
- the downstream extent of the river that would be significantly impacted by the proposed development;
- the length of river in which EFRs can be managed by, for instance, dam releases;
- international borders;
- the importance of the different river stretches involved (based upon their EMCs).

The study area is usually delineated prior to initiating the BBM study as it influences the study budget. It will therefore either be stipulated by the client or suggested by the consultant, and ratified during the Planning Meeting (Section 6.6). The EFR coordinator should be involved in this decision.

The study area is depicted on a diagrammatic map, for example as in Figure 6.1, which is then used throughout the study. All relevant information is added to it, such as the localities of the BBM sites when they are selected. This provides standardisation for all members of the study team.

6.4 PRELIMINARY SELECTION OF RIVER SECTIONS

The entire river length within the study area cannot be measured, mapped and characterised at a resolution appropriate to the riverine biotas. Sites within different kinds of river sections are thus used to represent the river as a whole.

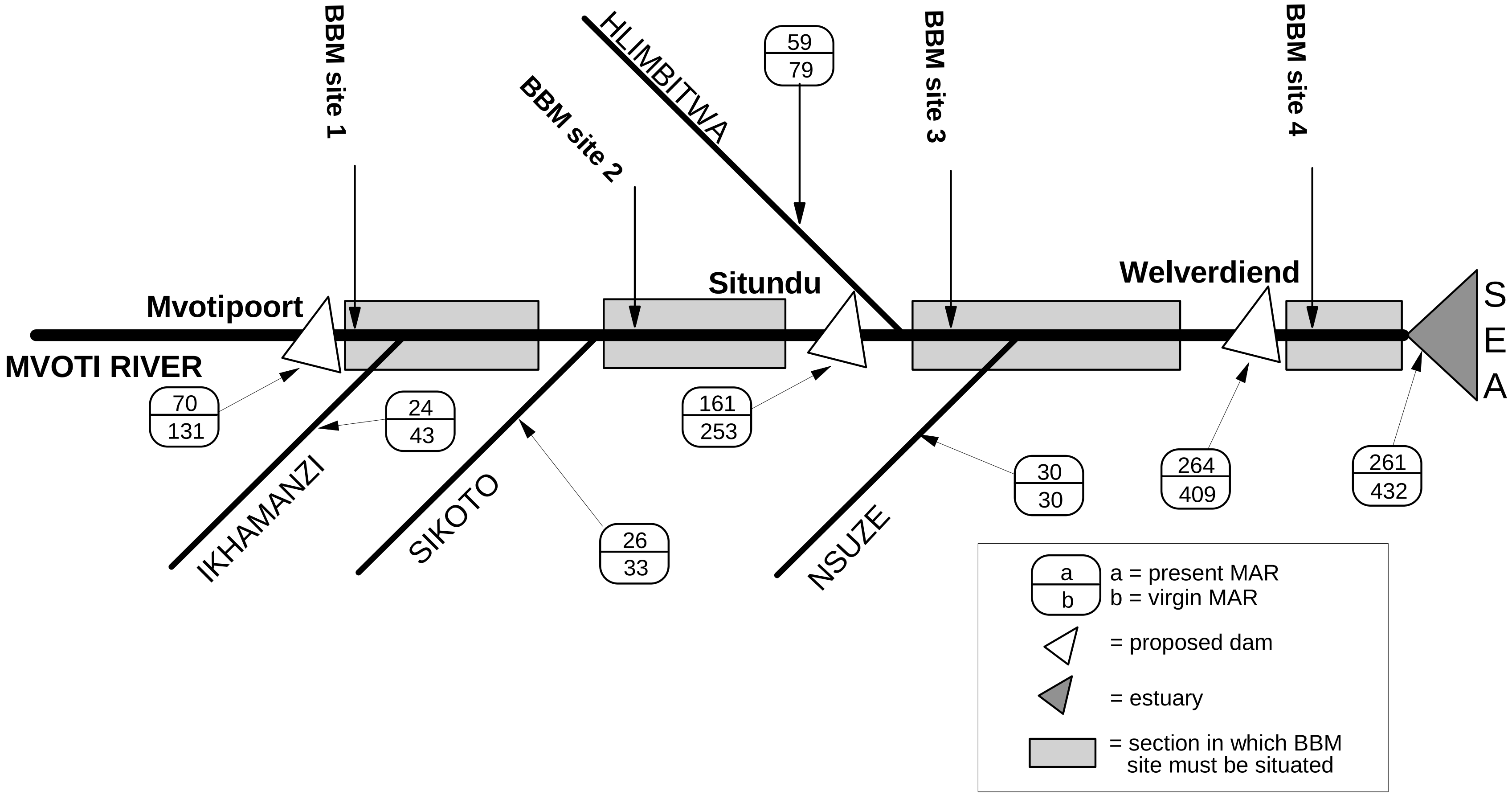

Figure 6.1 Diagrammatic map of the study area for the application of the BBM to the Mvoti River, from the most upstream dam option, Mvotipoort Dam, to the estuary. Rivers are indicated in capitals and proposed dam sites in lower case text. The four river sections within each of which a BBM site was located are indicated, as follows:

- **Section 1: Downstream of Mvotipoort Dam and upstream of the Sikoto Tributary.**
- **Section 2: Downstream of the Sikoto Tributary and upstream of Situndu Dam.**
- **Section 3: Downstream of the Hlimbitwa Tributary and upstream of Welverdiend Dam.**
- **Section 4: Downstream of Welverdiend Dam and upstream of the estuary.**

Chapter 14 describes the geomorphological, spatially-nested, hierarchical classification of rivers by segment, zone and reach. The BBM sections operate at approximately the same scale as segments (*sensu* Rowntree & Wadeson 1998, 1999). The selection of sections is guided by a geomorphological classification of the river, but the sections may or may not correspond to this classification when other criteria are also considered. Thus, knowledge of the distribution of different types of geomorphological reaches, and the representative reaches for each reach type, is tempered by such additional considerations as:

- a new section should begin immediately upstream of any major tributary, so that the previous, upstream section has flows described for it that do not rely on the tributary inflow (this ensures that each section of river has an EFR described for it);
- each proposed water-resource development should be within a different section, unless they are very close geographically, so that the implications for EFR releases from each one can be illustrated;
- there should be sufficient sections to reflect the increasing downstream runoff into the river, and the effect this has on channel form and functioning (the geomorphological classification should be used as a guide here).

The coordinator, and the team's hydrologist, geomorphologist and river ecologists, together delineate suggested sections, each of which should ultimately be represented by a site (Chapter 7). The sections selected will be used during the habitat integrity aerial survey (Section 6.5 & Chapter 8), and presented for final discussion at the Planning Meeting. The EFA for the Mvoti River provides a case example of the process of selecting river sections within which the BBM sites are located (Figure 6.1).

6.5 HABITAT INTEGRITY ASSESSMENT

Following delineation of the study area, a habitat integrity assessment is commissioned and completed. Details of this assessment are given in Chapter 8. Its relevance here is that before the aerial survey of the study area, river sections (Section 6.4) are provisionally delineated along all rivers in the study area, so that during the survey potential sites within each section can be sought (Section 7.3).

6.6 THE PLANNING MEETING

Once the habitat integrity assessment is complete, the coordinator organises a Planning Meeting. This brings together, for the first and perhaps only time before the BBM Workshop, the team of specialists appointed for the study:

- habitat integrity specialist;
- hydrologist;
- social scientist;
- workshop facilitator and/or coordinator;
- riparian vegetation specialist;
- fish specialist;
- aquatic invertebrate specialist;

- fluvial geomorphologist;
- hydraulic modeller.

While all the above specialists attend the Planning Meeting, only the last six attend the subsequent site selection field trip (Chapter 7).

The purpose of the meeting is to plan and initiate all further phases of the BBM study. Topics covered include:

- finalisation of the study area and river sections;
- review of available relevant information;
- description of further information needs;
- selection of representative reaches within sections, and number and tentative location of study sites;
- team coordination;
- preliminary plans for the workshop.

6.6.1 Aids required at the meeting

- 1:50 000 topographic maps with the 5 km habitat integrity sectors (see Chapter 8) marked.
- 1:250 000 topographic maps with the 5 km habitat integrity sectors (see Chapter 8) marked.
- Global positioning system (GPS) tracklog linked to the habitat integrity video.
- Diagrammatic map with the following marked: study area; potential and extant water-resource developments; major tributaries; and hydrological information such as natural and present MAR of all major tributaries and at points along the main river.
- Visual aids, including a television and video cassette recorder for running the habitat integrity video.

6.6.2 Agenda

The following is a typical agenda for the Planning Meeting. The agenda can be adjusted for any one study, but should include the points listed here.

- WELCOME
- PARTICIPANTS
- BACKGROUND TO THE STUDY
- PURPOSE OF THE MEETING
- ACTIONS REQUIRED FOR THE STUDY
- INFORMATION REQUIREMENTS
    - Study area
    - Available information and further information requirements
    - Ecological Management Class (Desired State)
        - Present Ecological State class (habitat integrity class)
        - River Importance
        - Preliminary Ecological Management Class
- PRELIMINARY SITE SELECTION
    - Description of the site selection process

    - Report on habitat integrity assessment
    - Geomorphological reach analysis
    - Biological zones
    - Representative reaches
    - Hydraulic suitability of prospective sites
    - Suitability of prospective sites for long-term monitoring programme
- ADDITIONAL DATA NEEDS AND REQUIRED LIAISON
- BBM WORKSHOP
    - Outline of the approach to be followed during the workshop
    - Participants
    - Contents of the workshop starter document
    - Date and venue of the workshop

After the Planning Meeting, the coordinator provides a written record to all attendees, and is then responsible for comprehensive coordination of the whole study. The next action is on-site ratification and final selection of the sites identified during the Planning Meeting (Chapter 7).

7. SELECTION OF STUDY SITES

Delana Louw and Nigel Kemper

7.1 THE IMPORTANCE OF STUDY SITES IN THE BUILDING BLOCK METHODOLOGY

The BBM sites are the focus for almost all data collection activities related to the BBM. The interests of some specialists, such as the ichthyologists, may range over longer lengths of river, but most will concentrate data collection within the sites. Additionally, the two vital ‘support services’ of hydrology (Chapter 12) and hydraulics (Chapter 13) provide information specifically for these sites, that the specialists use when converting their ecological or other environmental knowledge into a description of a recommended environmental flow regime (the EFR).

An EFR is set for each site, and there is usually only one site per river section. It is thus important that:

- each site provides the greatest range possible of the environmental conditions characteristic of the river section it represents;
- these conditions are represented in a way that the various specialists find acceptable and can use;
- the persons involved in selecting the sites understand and are experienced in the use of sites in assessments using the BBM.

7.2 MINIMUM AND IDEAL DATA SETS

More than one site is usually selected within the river system because:

- tributaries entering the system may introduce different channel, bank and or habitat conditions which will influence which plant and animal species can exist in the river;
- the EMC may differ for different stretches of river (Chapters 6 & 11), and each stretch will require an individual flow assessment;
- there is a transition of plant and animal communities along rivers which cannot adequately be represented by a single site.

The more sites selected, the better the chance that the full diversity of the system will be represented, and therefore the higher the confidence in the recommended EFR. However, the greater the number of sites, the more lengthy, complicated and expensive is the whole exercise. There is also a limit to the number of sites that can be considered within a BBM Workshop, as it takes about one day for the specialist team to describe an EFR for one site.

The final number of sites therefore reflects the length and diversity of the river system to be assessed, and is a tradeoff between the need to characterise the river adequately, and the constraints of time and resources.

7.2.1 Minimum data set

The minimum data set depends on the size and complexity of the study area. However, the following general principles apply:

- usually, most specialists cannot spare more than about four days from their normal work, or work effectively for longer than that in the intense activity of a workshop;
- four sites can usually be addressed by one group of specialists in a four-day workshop (i.e. eight sites could be addressed by two groups);
- based on past experience of applying the BBM, four sites, selected correctly, can be used to represent a river length of 100-200 km;
- a smaller study area does not necessarily translate into fewer sites, as the diversity of the system also has to be considered;
- there should be one site per river section.

7.2.2 Ideal data set

The ideal data set would be drawn from two sites for each river section, to allow within-section checking of flow recommendations. This is rarely possible within the cost constraints applied by the water resource developers.

7.3 SEQUENCE OF ACTIVITIES

Site selection is usually led by the BBM coordinator or a specialist familiar with the process. In this manual, it is assumed that the coordinator assumes this role.

To manage the site selection process, the coordinator should:

- have previous experience of how sites are used in a workshop;
- have an understanding of the contribution made by each discipline in the BBM, and of what characteristics each specialist will require at a site;
- be able to summarise the advantages and disadvantages of each potential site, to aid an informed decision on the final list of sites.

7.3.1 Use of the aerial survey to aid site selection

This activity takes place before the Planning Meeting (Section 6.6).

Locating potential sites in rugged and undisturbed surroundings can be a difficult, frustrating and time-consuming process. Most small access roads in rural areas are not marked on maps, and driving to all possible access points on both sides of the river could double the costs of site selection. Additionally, some good potential sites might be missed.

Site selection can therefore be aided by appropriate actions by the habitat integrity team during its aerial survey. Team members will already have been informed of the delineation of river sections and the need to locate at least one potential site per section (Section 6.5). They will then locate such sites, record their positions using a GPS unit, and capture both the sites and possible access routes on video. Additional verbal or written notes on access routes should be made, as the video may show only the close environs of the river. The person best suited to complete this task is the navigator (Chapter 8).

7.3.2 Identification of potential sites on the video

This activity usually takes place on the same day as the Planning Meeting.

The team members involved in site selection view the video. The persons involved are the BBM coordinator and those listed for site selection in Section 6.6. All of them should contribute to the exercise, in order to avoid selection of sites that are quite unsuitable for some disciplines. Having said this, selecting sites can often involve a tradeoff as, for instance, with a site that has physical features conducive to accurate hydraulic modelling, but that does not well represent the complexity of physical habitats that ecologists would like described.

From the video and the GPS data set, all potential sites can be accurately pinpointed on a map. These potential sites are then viewed on the video by the team. The objective is to eliminate some of the least suitable sites, leaving the most suitable for an assessment on the ground. Sites with complex hydraulics that cannot be modelled, or sites with poor access or poor representation from the perspective of some team members, might be eliminated at this stage. The team will then visit the remaining sites.

7.3.3 Groundtruthing - the final selection of sites, based on key criteria

This activity takes place immediately after the Planning Meeting, and can take three days or more.

The site selection visit should ideally occur at times of low flow (but not no flow), when features of the river bed and banks can be seen, and flow-sensitive areas such as riffles can be located. If time is limited (i.e. not extending till the next dry season), then the hydraulic cross-sections should be surveyed, and the initial stage-discharge measurements made, at the same time or immediately after the site selection visit (Chapter 13). This will allow improved resolution of the lower end of the stage-discharge curve.

Key criteria for site selection

A number of site attributes considered as desirable are assessed at each site, the most important of which are highlighted below (boldface):

- **easy access;**
- **high diversity of physical habitats at the site for aquatic and riparian species, and highly representative of the larger river section (see geomorphological analysis, Chapter 14);**
- **flow-sensitive habitat, and critical habitat for important species, even if this is not representative of the whole river section;**
- **suitable for accurate hydraulic modelling throughout the range of possible flows, and particularly of low flows;**
- close proximity of a gauging weir with good quality hydrological data;
- high potential of the site to provide useful EFR information, in terms of its location relative to the proposed water-resource development;
- site positioned upstream rather than downstream of a major tributary;
- good ecological condition, so that clues on flow-related features (such as vertical zonation of riparian vegetation up the banks) can aid understanding of the effects of different flows on the ecosystem;
- close proximity to human rural communities that utilise river resources for sustenance, and good representation in terms of those used resources (Chapter 9);
- potential as a later monitoring site.

Some reasons why a site may be deemed unsuitable are:

- located on a bend;
- located in a relatively featureless sandy stretch;
- consists mainly of a large pool (not flow-sensitive);
- located in an inaccessible gorge;
- possesses excellent habitat diversity and ecological condition, but it is not possible to model local hydraulics with confidence;
- several team members find the site of little use.

Although ideally, sites should be selected to be representative of a river section, it is more important that they should be at a critical point in the section. This means that they should exhibit flow-dependent features which, if satisfied, will ensure that the rest of the river section will be more than adequately provided for. For example, in a section with extensive pools and only one riffle, the site encompassing the riffle should be selected, since this would be the most critically flow-dependent place in the section.

7.3.4 Placement of cross-sections

After a site has been selected, the locations of cross-sections to represent the site are chosen. This is done by the whole team on site, guided by advice from the hydraulic modeller on the ability to accurately describe the local hydraulics of those locations. Specialists from different disciplines may desire different cross-sections, none of which are amenable to accurate hydraulic modelling, and the modeller may choose some cross-sections for modelling purposes that are not attractive to the other specialists. Compromises may need to be made, but agreement must be reached before leaving the site on the minimum number and location of cross-sections that will be used at the workshop.

Apart from the normal survey data on channel dimensions, other information will be required from each cross-section, and each specialist should state their needs clearly. These may include:

- the boundaries of vegetation zones up the banks;
- substratum and other details on physical habitat;
- vegetation and hydraulic cover.

Each site and cross-section is allocated a code number, which is reflected on the cross-section benchmarks set by the survey team. The most upstream site is BBM site 1 (previously also known as IFR1), with sites numbered consecutively downstream. The cross-sections for each site are designated with letters, with A being the most upstream one.

7.3.5 Other fieldwork completed during the site selection visit

Whilst in the field, it is cost effective to undertake some data collection exercises if time allows. Data that could usefully be collected at this time are listed below:

- **Cross-section dimensions and details**. During or immediately after the site selection trip, the selected cross-sections are surveyed.
- **Fixed-point photography**. A photographic record of a variety of known or measured flows is used extensively at the workshop, and so whenever discharge is measured, photographs of the river should also be taken. These should be taken at fixed points, preferably with the same camera, lens and lens setting, and should focus on the same stretch of river. Known cross-sections, particularly flow-sensitive ones, should be included in each photograph.
- **Hydraulics**. Once the cross-sections are surveyed, a first set of measurements of water surface elevation, discharge, and the distribution of water velocities and depths can be made (Chapter 13).
- **Fluvial geomorphology**. Hydraulic biotopes across the cross-sections are recorded, their hydraulic characteristics measured, and any features of importance noted for inclusion in the cross-section surveys (Chapter 14).

- **Riparian vegetation**. The riparian specialist marks and numbers trees and other vegetation for inclusion in the cross-section survey (Chapter 16).
- **River health and aquatic invertebrates**. A rapid assessment of river health can be done, using aquatic invertebrates and the South African Scoring System, SASS4 (Chutter 1998; Chapter 17).
- **Fish survey**. An early assessment of fish species present may be possible using an electroshocker. Detailed fish surveys follow later (Chapter 18).

7.3.6 Surveying the cross-sections

The hydraulic specialist supervises the survey team. Noting specialists' requirements as listed in Section 7.3.4 & 7.3.5, the cross-sections are surveyed, in order to be able to provide the following information on each surveyed cross-section at the workshop:

- a stage-discharge relationship, which will reflect the area inundated by any discharge;
- the position of vertical vegetation zones up the banks;
- the position of key plant species occur in these zones;
- the position of key geomorphological features, in order to establish the flows that inundate them or that are equivalent to, for instance, bankfull discharge.

7.4 THE SITE SELECTION REPORT FOR THE WORKSHOP

The above activities are documented by the BBM coordinator, to serve as a record of decision-making on site selection. This report is included in the workshop starter document. Different specialists may require specific information on each site. The coordinator ensures this is available, by asking the specialists to complete forms of relevant site information at each site. Recorded information will include, in a structured way, the advantages and disadvantages of each site from the specialist's perspective.

The contents of the site selection report include the following:

- purpose of the sites;
- selection of the sites;
    - study area
    - selection of river stretches
    - the helicopter flight: activities related to site selection
    - use of the aerial survey video
    - field visit: final selection of sites
- characteristics, advantages and disadvantages of each potential site, and final selection.

The report should include graphics such as Figure 7.1. It should be written immediately after the site selection trip, and distributed to all team members for reference in the ensuing work.

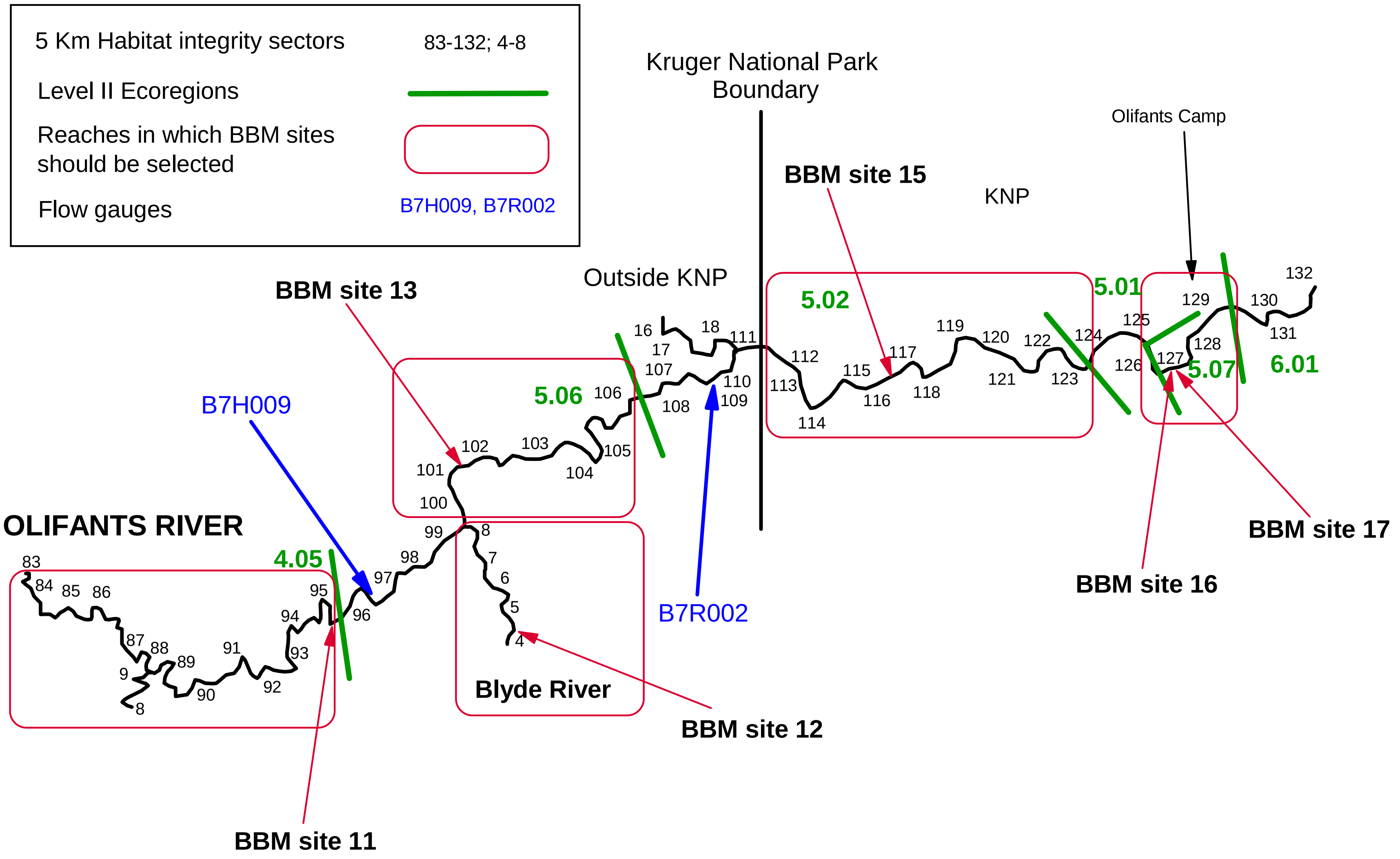

Figure 7.1 Illustration of river sections in which some BBM sites for the lower Olifants River are located (BBM sites 11-17; site 14 is on the Selati River). The mainstem Olifants River and tributaries, Kruger National Park, flow gauging stations level II ecoregions and 5 km sectors of the habitat integrity assessment are indicated (see Section 4.4 & Chapters 6-8, for further explanation).

8. OVERVIEW OF THE RIVER AND ASSESSMENT OF HABITAT INTEGRITY

Neels Kleynhans and Nigel Kemper

8.1 ASSESSMENT OF HABITAT INTEGRITY IN RIVER MANAGEMENT

Conceptually, biological integrity is a measure of an ecosystem’s ability to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity and functional organisation comparable to that of the natural habitat of the region (Karr & Dudley 1981). On the other hand, the concept of habitat integrity, at least for rivers, reflects the degree to which, temporally and spatially, a balanced, integrated composition of physical and chemical characteristics has been maintained compared to those of undisturbed rivers of the region. Essentially, the habitat integrity status of a river will provide the template for a certain level of biotic integrity to be realised. Thus, assessment of the habitat integrity of a river can be seen as a precursor to the assessment of biotic integrity. It follows that in this context, habitat integrity and biological integrity together constitute ecological integrity (Kleynhans 1996).

8.2 ASSESSMENT OF HABITAT INTEGRITY IN THE BUILDING BLOCK METHODOLOGY

In the context of the BBM, the purpose of an assessment of habitat integrity is to provide a general indication of the current ecological condition of the whole or part of a river, as measured against a hypothetical natural situation. Since the EFRs are assessed at particular sites along the river, the habitat integrity assessment serves to illustrate the context of the sites along the whole length of the study area, for example, to check what artificial structures there may be upstream and/or downstream of the site that might affect its flow characteristics. Together with inputs on the ecological importance of the river (Chapter 10), this information is then used in the determination of the desired EMC (Chapter 11), the attainment and maintenance of which is the objective in the setting of an EFR for the river. Information on the habitat integrity status of a river can also be used to indicate the general nature of ecological problems in the river, and can contribute to assessing the potential for achieving a specific EMC.

In the BBM, habitat integrity assessments are based on videographic, low-altitude aerial surveys of the river, which provide a considerable amount of information on, and insights into, the characteristics and present condition of the river. Helicopters are used for the surveys because of the large areas covered, the possibility of difficult terrain, and the fact that large parts of many rivers are largely unknown. Despite the relatively high operation cost, helicopter surveys are an efficient way to obtain information on the general condition and characteristics of rivers in a relatively short time. Additionally, the manoeuvrability of a helicopter, and its capability of flying fairly safely at low altitudes and low speeds, makes it possible to obtain information from relatively inaccessible areas.

8.3 SEQUENCE OF ACTIVITIES

The sequence of events described below is based on the understanding that the study area has been identified and the primary concerns regarding the river known. These concerns may include defining which sections of the river are of major concern with regard to the proposed water-resource development, which sections should be represented by a BBM site and which are the major ecosystem components under threat (see Chapter 7).

8.3.1 Preparation for the aerial survey

This first activity is the responsibility of the navigator.

- The length of river to be surveyed is determined. 1:250 000 or 1:50 000 maps are suitable for this purpose. If adequate funds are available, it is preferable to survey the entire river from source to either the estuary or the most downstream point likely to be impacted by the development of concern. However, depending on the nature of proposed developments for the river, and on budgetary constraints, it may be possible or necessary to survey only selected reaches of the river.
- The requirements regarding the helicopter and pilot experience are specified. The helicopters best suited for river survey work are the Bell Jet Ranger or Hughes 500, as these are able to carry two to three passengers at a variety of altitudes with sufficient fuel for at least two and a half hours of flying. They can also negotiate tight turns with adequate stability for videographic purposes. Videography is undertaken with the back door of the helicopter removed. The seats should be sufficiently comfortable to work from for several hours, and be fitted with a suitable safety harness. An intercom system that serves all passengers and the pilot should be standard equipment. The survey should be undertaken by the charter company as an organised charter operation, because plain ‘hire and fly’ operations do not offer adequate safety and insurance for the survey team. Indemnity insurance to adequately cover the lives of the survey crew should be carried by the charter company. Usually cover is taken to an amount of two million Rand per passenger. The pilot should have at least 2000 hours of helicopter experience and should be extensively experienced with low-level flying operations.
- Early quotations for helicopter costs are obtained from the charter company. Logistics of the flight should then be determined carefully in order to establish the total costs of the survey. Apart from the costs of the survey itself, the ferry costs to and from the survey area have to be considered, as these are often a large component of the total costs. The time required for the survey should be based on an air speed of approximately 70 km h^{-1}. The ferry time required to reach the study area and return should be based on an airspeed of approximately 160 km h^{-1}. If the survey is government funded, adequate time should be provided prior to the survey to obtain information about the charter company which has the contract to undertake the work. If no company is contracted in, or the company does not have the appropriate equipment for the survey, it will be necessary to search for and appoint a suitable company. This can take several weeks.
- Flight logistics are discussed with the pilot several days prior to the survey, to ensure that the videographic requirements can be met, suitable refueling points arranged, and staff and fuel made available at these points. Jet A1 fuel or paraffin is not available at all airfields and it is usually better, given the cost to ferry the helicopter to nearby airfields, to organise that the fuel is where it is needed en route. It is advisable that weather conditions are monitored for several days before the planned survey date, and that other days are reserved should poor weather conditions occur on the planned day of the survey.

8.3.2 Planning the survey

This activity is the responsibility of the navigator.

- 1:250 000 or 1:50 000 (if available) topographic maps of the river section are obtained.
- Consecutive 5 km-long sectors of river are demarcated on the maps to be used for the survey. These sectors are numbered starting from the point furthest upstream. Where possible, distinctive features such as road

bridges should be used to demarcate sector breaks, as this will assist with navigation during the survey.

- The coordinates of all 5 km sector breaks are determined and stored on a GPS. This step is vital if 1:50 000 maps of the survey are not available, particularly if the survey will cover rough terrain.
- The group responsible for site selection (Chapter 7) is requested to make preliminary suggestions on the general areas where sites should be located.
- Discussions are held with the pilot regarding refueling points and times, and overnight accommodation if necessary. Responsibilities are decided upon for ground support teams.

8.3.3 Preparation of video equipment

This activity is the responsibility of the videographer. The following need to be acquired:

- A video camera. The minimum requirement is a Panasonic VHS analog camera with a x14 zoom and digital image stabilizer. If possible, the camera should be able to display hours, minutes and seconds, in order to synchronize with the GPS tracklog. A backup camera is desirable, and cost effective compared to repeating the flights due to a camera malfunction.
- A sealed 12 V compact battery pack, with a cigarette-lighter type socket and a suitable cable to supply power from this battery pack to the camera. Such a battery pack should provide in excess of five hours of video time. A spare battery pack should also be obtained and it should be ensured that both are fully charged shortly before the survey. Such a battery pack (usually used for hunting lamps) is not a standard accessory for video cameras, and can be obtained from dealers in camping equipment.
- A sufficient number of video camera cassettes, plus two or three spares. Cassettes with a recording capacity of one hour are preferable.
- A small clip-on microphone, with a 2-3 m extension cable that can be plugged into the video camera.

The videographer must be well versed in the operation and limitations of the video equipment.

8.3.4 Pilot's instructions

Prior to the flight, the videographer and navigator should discuss survey details with the pilot, including the following:

- **The altitude at which the survey is conducted**. This will vary depending on the width of the river. Usually, however, surveys are done at an altitude of 50-100 m.
- **The way in which the survey will be conducted**. Usually the videographer sits in the right-hand back seat of the helicopter and the survey is done while flying downstream. To obtain a recording of details on both river banks, the pilot should fly along the left-hand bank and also bias the front of the helicopter slightly towards the left to provide the videographer with the best possible view of the river. Surveys are usually done at an air speed of approximately 70 km h^{-1}.
- **Specific flying requirements**. At times, the pilot may be instructed to circle and/or hover the helicopter, in order for the videographer to capture particular details or to change video cassettes.

8.3.5 Functions of the navigator during the survey

It is strongly recommended that an aquatic ecologist with some previous experience of helicopter surveys and of aerial navigation be used as navigator. The navigator should do the following:

- Use the prepared maps as well as the GPS to navigate. The GPS tracklog should be recorded in conjunction with the video footage to ensure that tracklog coverage is available for all video footage.
- Call out over the intercom the number of each 5 km sector as the helicopter moves into it.
- Make observations into the video camera microphone of relevant features, such as the presence of exotic plant species, disturbed areas (erosion) or agricultural land use. The microphone should be attached to the navigator's intercom microphone.
- Continuously check that the pilot is positioning the helicopter to provide the videographer with the best possible view. Particular attention should be paid to the height, the airspeed and the forward bias of the helicopter.
- Be on the lookout for potential BBM sites within sections of interest, which will aid the final selection of sites. Features that make a site potentially useful are:
    - riparian vegetation in good condition;
    - diverse aquatic habitats (pools, rapids, riffles, runs);
    - channel amenable to hydraulic modelling (not too complex);
    - accessibility.

  If such a site is found, the helicopter should circle, the coordinates should be recorded, and the videographer asked to record the details of the site.
- Warn the pilot of any obstructions (e.g. cables) across the river.
- Ensure that regular breaks are taken. These will enhance concentration and prevent exhaustion. Usually a maximum stretch of one to one and a half hours of continuous recording between breaks should be aimed for. The total video recording time per day should preferably not exceed five to six hours.
- After completion of the survey, provide a hardcopy of the tracklog and a GPS map of the flight path to the habitat integrity assessor. The tracklog should indicate the camera-synchronised time of the survey, together with the coordinates of the flight path and the sector breaks. The tracklog may require some editing to remove unwanted track data and simplify the flight path map.

8.3.6 Functions and requirements of the videographer during the survey

It is strongly recommended that an aquatic ecologist with previous experience of the operation of a video camera from a helicopter be used as videographer. The videographer should:

- Videograph from the right-hand back seat of the helicopter while flying downstream.
- Point the camera toward the front of the aircraft and slightly down.
- Ensure the time and date indicators of the camera are turned on when recording. The camera's clock should be synchronized as closely as possible with that of the GPS. This will make it possible to locate particular points along the river on the video with some accuracy.
- Check the camera regularly to ensure it is actually recording.
- At the start of the survey or when a new cassette is inserted, make a voice recording of the name of the river.

- When a new cassette is inserted, number the one that is removed and store it in a secure place.
- Ensure that both riverbanks and the channel itself are recorded on the video. The pilot should be instructed to position the helicopter correctly to make this possible, and in order to limit inclusion of parts of the aircraft on the video.
- Repeatedly look up from the camera's viewfinder to ascertain if important river features (e.g. degraded areas, weirs, exotic vegetation, pumps, rapids, riffles, erosion dongas) are being approached. These features may be zoomed in on. A zoom strength of 3-4x is suitable for use from a moving helicopter. The digital-image stabilizer should be checked to ensure it is activated during recording.
- Make recordings of the wider area along the river from time to time in order to gain an impression of landscape features. If necessary, the pilot should be requested to increase the altitude and circle in order to obtain a better perspective of the landscape.
- When cassettes or batteries are being changed, ask the pilot to circle until recording can recommence.
- When the navigator indicates that the aircraft is moving into the next sector, point the camera at the roof of the helicopter and call out the sector number. This facilitates rapid location of sectors on the cassette when rewinding or fast-forwarding on a video cassette recorder. If a clip-on microphone is used, the navigator records the sector number directly onto the cassette.

8.3.7 Copying camera cassettes onto video recorder cassettes

- It is strongly recommended that after completion of the survey, the camera cassettes are copied onto video recorder cassettes, which should be clearly labelled "master copy". The three- to four-hour video cassettes are more convenient to work from. The original camera cassettes should be clearly labelled and safely stored.
- A copy of the video should be provided to any member of the specialist team who requests it, but particularly to the geomorphologist and the group responsible for the selection of BBM sites.

8.3.8 Assessment of video material

The navigator and videographer usually perform this activity. The navigation maps and GPS tracklog are referred to when viewing the video material.

- In an uninterrupted familiarisation run, the video recording is first viewed at normal playback speed, without making notes or reviewing any part.
- In a second run, the cassette is stopped and details of the river viewed as necessary, with notes made on the characteristics of each sector. Also, notes are made of disturbances such as the number of weirs, disturbed areas, land use (towns, squatter areas, agriculture, plantations), pumps, roads, bridges, erosion, exotic macrophytes, exotic riparian vegetation, trampled areas, and so on, with some qualitative indication of their commonness or the severity of change from natural (Kleynhans 1996).
- During the second run, the natural attributes of the river also are noted, and the geomorphological zonation of the river commented on.
- Following the detailed viewing, an additional perspective of riverine condition is gained by playing the cassette at high speed at least twice, with stops to review particular sectors or points.

- As a final step, a short, edited copy of the survey video recording is made, indicating the most important relevant aspects in terms of the habitat integrity of the river. This summary version is shown to the full BBM team during the workshop (Section 7.3), and so should preferably not be longer than 30 minutes.

8.3.9 River zonation

Based on information available from topocadastral maps as well as from the video, the river is categorised into geomorphological zones following the basic approach of Rowntree & Wadeson (1998). The purpose is to create a broad classification of the river that can be related to the general riparian and instream habitats present. The approximate positions of these zones are indicated on a map and the 5 km sectors present are demarcated.

8.3.10 Groundtruthing

Following the aerial survey, selected points along the river are visited as necessary, to obtain specific information on aspects such as those indicated under Section 8.3.11.

8.3.11 Rating of habitat integrity

Based on the information obtained from the video recording, as well as all available information as indicated in Section 8.4, the habitat integrity is assessed per sector and summarised per river zone.

The methods used in the collation and interpretation of data and the rating and final assessment of habitat integrity are elaborated on in Kleynhans (1996). In essence, the procedure involves the separate assessment of instream habitat integrity and riparian habitat integrity according to a number of key modifiers (Table 8.1). The observed or deduced condition of each modifier, compared to what it could have been under unperturbed conditions, is surmised, to indicate the degree of change from natural habitat integrity. A rating system is devised (Table 8.2), based on different weights for each modifier (Table 8.3) that reflect their perceived importance in determining habitat integrity. This rating system is used to assess the total habitat integrity for the instream and riparian components of the river. The final sum of the modifiers for the riparian component, and the water abstraction, flow modification, bed modification, channel modification, water quality and inundation modifiers for the instream component, receive additional weights if impacts on these modifiers were considered large, serious or critical. The sum of these ratings is used to classify the instream and riparian zone components according to a descriptive integrity class (Table 8.4). An assessment and rating system has been developed in spreadsheet (QuattroPro for Windows) format to facilitate this assessment. A copy of this software application is available from the authors.

8.4 MINIMUM AND IDEAL DATA SETS

8.4.1 Ideal data set

The ideal data set for an assessment of habitat integrity would include the following components.

- Catchment information such as contained in the catchment study reports of DWAF.

- Definition of sections of the river that are ecologically different in terms of natural conditions and current development. This would be provided during the Planning Meeting, using available biological, geomorphological and physiographic information (Sections 5.3 & 6.6).

Table 8.1 Modifiers used in the assessment of habitat integrity.

MODIFIER	RELEVANCE
Water abstraction	Direct impact on habitat type, abundance and size. Also implicated in flow, bed, channel and water quality characteristics. Riparian vegetation may be influenced by a decrease in the supply of water.
Flow modification	Consequence of abstraction or regulation by impoundments. Changes in temporal and spatial characteristics of flow can have an impact on habitat attributes such as an increase in duration of the low flow season, resulting in low availability of certain habitat types or water at the start of the breeding, flowering or growing season.
Bed modification	Regarded as the result of increased input of sediment from the catchment or a decrease in the ability of the river to transport sediment (Gordon *et al*., 1992). Indirect indications of sedimentation are stream bank and catchment erosion. Purposeful alteration of the stream bed, e.g. the removal of rapids for navigation (Hilden & Rapport 1993), is also included.
Channel modification	May be the result of a change in flow, which may alter channel characteristics causing a change in marginal, instream and riparian habitat. Purposeful channel modification to improve drainage is also included.
Water quality modification	Originates from point and diffuse-point sources. Measured directly, or its likelihood indicated by agricultural activities, human settlements and industrial activities. Aggravated by a decrease in the volume of water during low or no-flow conditions.
Inundation	Destruction of riffle, rapid and riparian habitat. Obstruction of the movement of aquatic fauna and influences water quality and the movement of sediments (Gordon *et al*., 1992).
Exotic macrophytes	Alteration of habitat by obstruction of flow and may influence water quality. Dependent upon the species involved and scale of infestation.
Exotic aquatic fauna	Disturbance of the stream bottom during feeding may influence water quality and increase turbidity. Dependent upon the species involved and their abundance.
Solid waste disposal	A direct anthropogenic impact which may alter habitat structurally. Also a general indication of the misuse and mismanagement of the river.
Vegetation removal	Impairment of the buffer zone that riparian vegetation forms against the movement of sediment and other catchment runoff products into the river (Gordon *et al*., 1992). Refers to physical removal for farming and firewood, and to overgrazing. Includes both exotic and indigenous vegetation.
Exotic vegetation encroachment	May eradicate natural vegetation, due to vigorous growth, which causes bank instability and decreases the buffering function of the riparian zone. Allochthonous organic matter input also changed. Riparian habitat diversity also reduced.
Bank erosion	Decrease in bank stability causes sedimentation and possible collapse of the riverbank, resulting in a loss or modification of both instream and riparian habitats. Increased erosion can be the result of natural vegetation removal, overgrazing or encroachment of exotic vegetation.

- Up-to-date and reliable information on the hydrological characteristics of each defined river section, including daily flow data for selected BBM sites in the different river sections. This information will usually be provided by the hydrologist appointed for this function (see Chapter 12).
- Recent low-altitude videography of the river from the source downstream to the sections being investigated (this chapter).
- Representative water quality data for all the different sections of the river, with particular reference to those physical and chemical variables of major ecological relevance. These data should be limited to general indicators such as conductivity, pH, total suspended solids (TSS), and oxygen and nitrate concentrations. The DWAF water quality guidelines for aquatic ecosystems can be used to provide some indication of the constituents that may be of importance, when the activities taking place in the catchment are considered. In South Africa, general information on water quality can be found in the relevant water quality database of DWAF, or interpretations may be provided by a water quality specialist appointed for this purpose (see Chapter 15).
- Satellite imagery of the river's catchment.
- Comprehensive and recent survey information on the riparian and instream biotas and their flow-related habitat requirements.

Table 8.2 Descriptive classes for the assessment of modifications to habitat integrity.

IMPACT CLASS	DESCRIPTION	SCORE
None	No discernible impact, or the modification is located in such a way that it has no impact on habitat quality, diversity, size and variability.	0
Small	The modification is limited to very few localities, and the impact on habitat quality, diversity, size and variability is also very small.	1-5
Moderate	The modifications are present at a small number of localities, and the impact on habitat quality, diversity, size and variability is also limited.	6-10
Large	The modification is generally present with a clearly detrimental impact on habitat quality, diversity, size and variability. Large areas are, however, not influenced.	11-15
Serious	The modification is frequently present and the habitat quality, diversity, size and variability of almost the whole of the defined area are affected. Only small areas are not influenced.	16-20
Critical	The modification is present overall with a high intensity. The habitat quality, diversity, size and variability of almost the whole of the defined section are influenced detrimentally.	21-25

8.4.2 Minimum data set

The minimum data set for an assessment of habitat integrity would include the following components.

- General information on land use in the catchment.
- General information on the hydrological character of the river, i.e. general information on the extent of water abstraction and flow regulation.
- Videography, or at least low-level aerial photography, for the section of the river under investigation.

- Some water quality information, or an informed judgment on the water quality as related to the structure and functioning of the aquatic ecosystem.
- Some information on the aquatic biota or at least an informed opinion on the attributes of the biota in the river section.

Table 8.3 Weights of modifiers used for the assessment of instream and riparian habitat integrity.

INSTREAM MODIFIER	WEIGHT	RIPARIAN MODIFIER	WEIGHT
Water abstraction	14	Bank erosion	14
Water quality	14	Indigenous vegetation removal	13
Bed modification	13	Water abstraction	13
Channel modification	13	Water quality	13
Flow modification	13	Exotic vegetation encroachment	12
Inundation	10	Channel modification	12
Exotic macrophytes	9	Flow modification	12
Exotic fauna	8	Inundation	11
Solid waste disposal	6		
TOTAL	**100**	**TOTAL**	**100**

Table 8.4 Classes for the assessment of habitat integrity.

CLASS	DESCRIPTION	SCORE (% OF TOTAL)
A	Unmodified, natural.	100
B	Largely natural with few modifications. A small change from natural in habitats and biotas may have taken place, but the ecosystem functions are essentially unchanged.	80-99
C	Moderately modified. A loss of and change from natural habitats and biotas has occurred, but the basic ecosystem functions are still predominantly unchanged.	60-79
D	Largely modified. A large loss of natural habitats, biotas and basic ecosystem functions has occurred.	40-59
E	The losses of natural habitats, biotas and basic ecosystem functions are extensive.	20-39
F	Modifications have reached a critical level and the lotic system has been completely modified, with an almost complete loss of natural habitats and biotas. In the worst instances, basic ecosystem functions have been destroyed and the changes are irreversible.	0-19

8.5 STARTER DOCUMENTATION FOR THE WORKSHOP

This component of the starter documentation for the workshop should include concise information on the habitat integrity of all parts of the study area, as well as conclusions regarding the main reasons for the habitat integrity status of the river. The report should follow the normal structure of such a document, with the following sections: introduction, study area, method, results, discussion, and conclusions. The following should be included in the body of the document:

- A map indicating flight sectors, geomorphological zones and all relevant detail.
- Graphs indicating changes from natural in the hydrological character of the river, at points for which data are available. Aspects of particular importance can often be found in FDCs of daily or monthly flow (Chapter 12).
- Relevant water quality data and information. These can be tabulated if necessary (Chapter 15).
- Tables of modifiers for the riparian and instream components, indicating the main ones per sector or geomorphological zone (e.g. Table 8.1).
- Graphs indicating the ratings for the different modifiers for the riparian and instream components, per sector or geomorphological zone. The graphs are generated automatically by the spreadsheet application mentioned in Section 8.3.11.
- Graphs indicating the integrity class assessment for the riparian and instream components (Table 8.4) per sector or per geomorphological zone. These graphs are generated automatically by the spreadsheet application. A graphic can also be produced to illustrate the results (e.g. Figure 8.1).

The purpose of the document is to enable workshop participants to gain a first understanding of the present condition of the river, the degree of change from its natural condition, and the main reasons for the change. Eventually, this information will be used to aid decisions on an attainable EMC for the river.

8.6 ROLES AND RESPONSIBILITIES AT THE WORKSHOP

At the BBM Workshop, a presentation of the habitat integrity status of the river should be given. With the understanding that the participants have read the starter document, only the main points should be indicated and maps and graphs used to aid in this process. Due to time constraints, the edited version of the video recording should be shown to the workshop participants. The presenter of the habitat integrity report should ensure that sufficient relevant comment and explanation is given while showing this video.

8.7 ROLES AND RESPONSIBILITIES AFTER THE WORKSHOP

As a result of its early position in the process, the assessment of habitat integrity is often done without access to information emanating from other work being done for the workshop. Comprehensive information on river geomorphology and zonation, and on water quality, is often unavailable at this early stage. Information on hydrology is usually provided during the assessment of habitat integrity, but additional information on this and other aspects may also only become available during or shortly before the workshop. This additional information may influence the ratings of individual impacts and thus the final habitat integrity classes. It may be necessary, therefore, to reassess aspects of the habitat integrity assessment before its inclusion in the final documentation of the workshop proceedings.

8.8 EXAMPLE OF TERMS OF REFERENCE

The Terms of Reference for the assessment of habitat integrity should contain the following directives:

- Delineate accurately the part of the river being investigated. Include, if necessary, parts of the river upstream and outside the direct area of impact of any planned development.
- Provide specific instructions that the survey should be based on a low-altitude helicopter survey (50-100 m altitude). Recognise that groundtruthing may be required at selected points.
- Produce the following:
    - Topocadastral maps (1:250 000 and 1:50 000 if available) of the study area.
    - River lengths delineated and numbered as 5-km long sectors on these maps and suitable for navigation purposes. Provide the coordinates of both upstream and downstream points of each 5 km sector.
    - Delineation of the river into geomorphological zones, using an acceptable classification system. Provide maps and documentation of this classification.
    - A continuous low-altitude video recording of the river. This video should include both the instream and riparian aspects of the river and must be cross-referenced with the navigation maps. The numbering of 5-km river sectors should be voice-recorded on the videocassette. A specified number of copies of the original video recording should be made.
    - From the survey, provide information and detail on possible BBM sites. Videographic tapes and still photography of such sites are required. Record and report on the coordinates of such sites, and well as their accessibility.
    - Calculations of the instream and riparian zone habitat integrity of the river for each sector and geomorphological zone. Report these according to approved procedures and methodologies. Apart from information originating from the river survey, all other available information sources should be consulted for the assessment of habitat integrity.
- Report on the results of the survey and the habitat integrity assessment during the BBM Workshop. Include presentation of the edited (30 minute) video recording of the survey.
- Be prepared to adapt the report on the habitat integrity assessment, based on information that comes to light during the workshop.

8.9 MINIMUM AND OPTIMUM SPECIALIST TRAINING

It is strongly recommended that an aquatic ecologist with some previous experience of helicopter surveys and aerial navigation be used as navigator. The minimum requirement is a person with some aerial navigation experience.

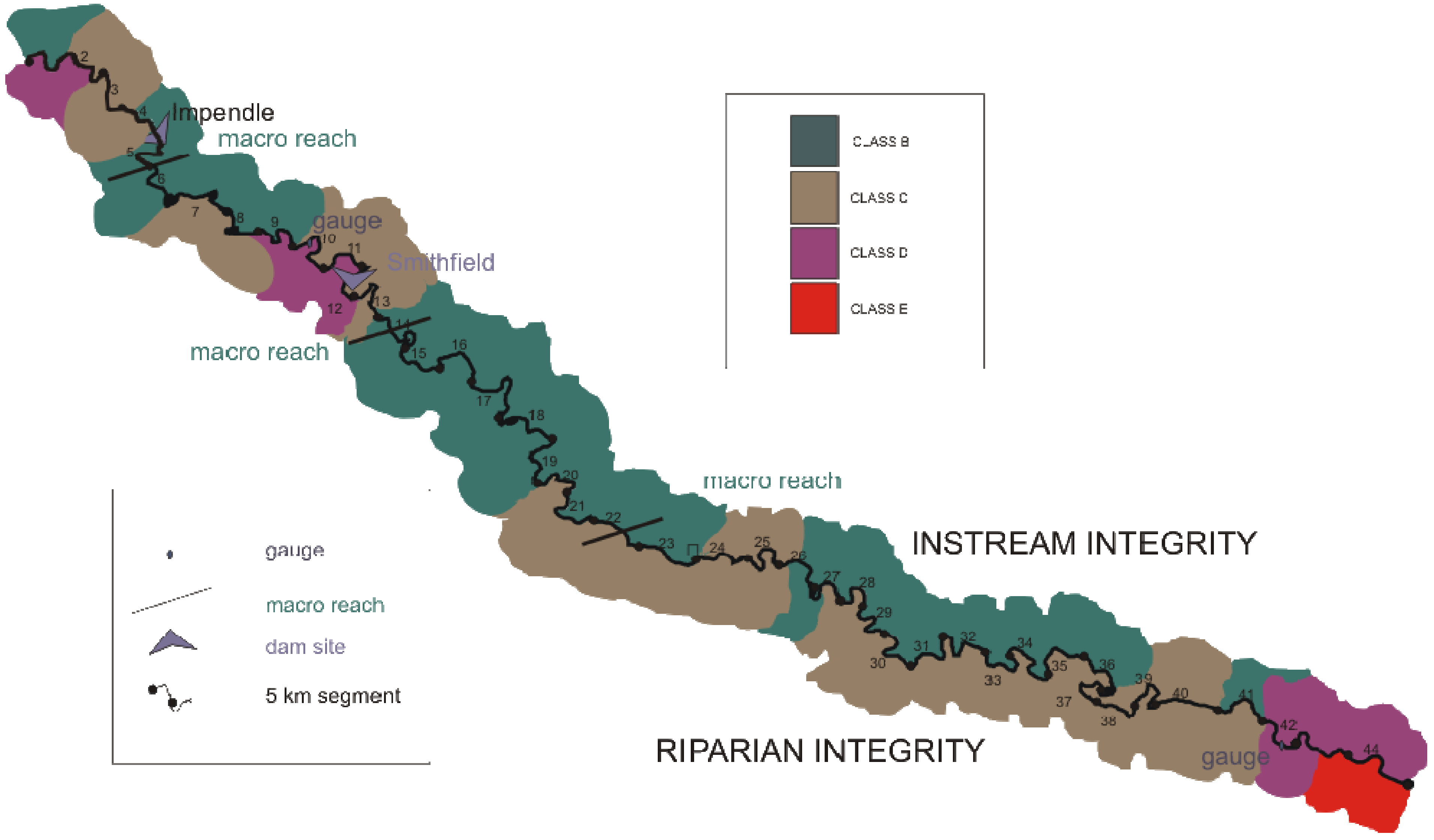

Figure 8.1 The habitat integrity of the Mkomazi River, indicating 5 km sectors and instream and riparian zone integrity classes.

It is strongly recommended that an aquatic ecologist with previous experience in the operation of a video camera from a helicopter be used as videographer. The minimum requirement is an experienced videographer who is not an ecologist but who has been instructed on the required product, or an ecologist with little experience of videography but who understands what is required. The videographer must be able to video-record for extended periods of time from an open helicopter door.

The person who eventually uses the survey data to make the habitat integrity assessment should be an aquatic ecologist, preferably with experience of the methodology and first-hand knowledge of the river. Ideally, the assessor should be an experienced ecologist, and either the videographer or navigator during the survey. The minimum requirement for the assessor is an aquatic ecologist with access to the advice of another aquatic ecologist who is experienced in the methodology. In such a situation, it is also essential that the experienced aquatic ecologist discuss particulars of the river with the navigator or videographer.

8.10 POTENTIAL PITFALLS

Helicopter surveys are expensive. It is important to take along backup equipment such as a spare camera, extra video cassettes and a spare battery.

Bad weather conditions can make aerial surveys impossible. It is important to obtain medium-term weather forecasts prior to the start of the survey, and make timely decisions based on this information. Adequate time and contingency plans should exist, in case bad weather delays the survey.

If possible, surveys should only be done during the dry season. Apart from bad weather conditions during the rainy season, the riparian vegetation may be so dense and the flow so high at this time that only limited observations are possible.

8.11 FURTHER DEVELOPMENTS

It can be expected that technological developments will improve the quality of video recordings considerably (i.e. digital video cameras, GPS links to the video camera and the storage of video recordings in CD-ROM or DVD format). In addition, low-level aerial photography and satellite imagery will probably be applied more extensively in the future.

The methodology for the assessment of habitat integrity should be improved. Presently, it is based on a simplified, fundamental understanding of the relationship between certain environmental modifications and changes in aquatic habitat. As this understanding and insight improves it will be possible to establish clearer links between these variables. The development of indices to assess the impacts of changes in, *inter alia*, hydrology, water quality and bed characteristics, is already underway. Such indices will have to be integrated into an overall assessment index of habitat integrity.

8.12 MONITORING

In South Africa, it is expected that monitoring of habitat integrity based on aerial surveys will only be undertaken when a river has been targeted for major water-resource development or when some extensive degradation of the river is suspected. In conjunction with additional information sources, the habitat integrity assessment will represent the current baseline habitat integrity for the river. However, once rivers have been prioritised, based on ecological importance and sensitivity, and on development pressure, it is envisaged that they will be surveyed according to a program. In general it is expected that monitoring in this way will be done with a time interval of three to five years.

After environmental flows have been specified and are being delivered, monitoring of biological, hydrological, water quality and other aspects should take place to assess if the desired EMC (see Section 4.5) for the river is achieved. Assessment of habitat integrity can be part of this assessment, or it can occur in response to particular monitoring results. Generally, the habitat integrity assessment will reflect changes at the meso-scale (spatially and temporally), compared to monitoring of the chemical, physical and biological aspects, that will tend to reflect micro-scale changes. The response of the riparian zone and the instream component due to a particular flow specification may, therefore, only be reflected in habitat integrity assessments after a number of years.

Apart from its significance in the BBM, habitat integrity surveys also form part of the National River Health Programme (Roux 1997). Within this programme, habitat integrity assessments may be repeated at intervals, if the biomonitoring results warrant this.

8.13 CONCLUSIONS

There is considerable room for improving both the data gathering techniques and the methodology for the assessment of habitat integrity. Nevertheless, the assessment forms an important part of the BBM by providing early and rapid information on the ecological condition of the river. The visual record of habitat integrity conditions provides a source of information that did not exist previously, and becomes a valuable historical record of the river.

9. SOCIAL USE OF RIVERINE RESOURCES

Sharon Pollard

9.1 RESOURCE USE IN RIVER MANAGEMENT

Recent approaches to river management in South Africa subscribe to a holistic ecosystem-based approach, in contrast to some other countries, such as the U.S.A. for example, where management objectives are frequently governed solely by the need for maintaining fisheries. The South African approach to river management reflects the recognition that a far greater range of factors is involved in the functioning, and thus management, of river systems.

One such factor encompasses the social dimension, an area that has been largely ignored in most countries. Even South Africa's most recent attempts to address "social issues" within the water sector are focused on the provision of water for basic domestic requirements. There is however, another aspect to this social dimension that is emerging from the field of terrestrial ecology - that of the importance of natural resources in sustaining peoples' livelihoods. Recent studies of the economic importance of formal and informal activities in local economies demonstrate this point. One case study, conducted in the Bushbuckridge district of Mpumalanga Province, South Africa, indicated that the economic returns from so-called "informal" harvesting of natural resources were **three times** as high as those from the formal sector (an estimated R17 million per annum compared to R6 million, respectively; see C. Shackleton, in Pollard *et al.*, 1998). Likewise, the critical role of riverine resources (both instream and offstream) in sustaining rural communities has been repeatedly demonstrated by, for example, the loss of floodplain soils and fisheries resources to peoples downstream of the Aswan High Dam in Egypt (McCully 1996), or the Josini Dam in South Africa (J. Venter, Environmental Services, Klaserie, pers. comm.). Thus, as South Africa moves into an era of more inclusive and comprehensive understanding of factors influencing our society, the onus is on researchers to provide an accurate and integrated picture of the linkages between people and the resources that sustain them.

9.2 RESOURCE USE IN THE BUILDING BLOCK METHODOLOGY

The objective of the social assessment in the BBM is to provide information on the use of riverine resources by rural communities, and on the importance of a healthy riverine ecosystem, from a community perspective, for sustaining their livelihoods. In essence, this involves understanding with communities the importance of, and their reliance on, run-of-river flow for providing resources such as fish; riparian plants for food, thatching, medicinal and other purposes; and areas of multiple use such as floodplains and pools. The social assessment used in the BBM differs from other, more conventional sociological assessments in that it not only requires describing the resources that are used, but also their ecological identities and relevance in terms of riverine ecosystem functioning. The challenge facing those compiling information for this part of the BBM study is to provide an ecosystem link to the sociological assessment, with all resources used identified to species and their use quantified. Finding ways to understand and capture peoples' perceptions regarding the relationship between river flow and resources, as well as historical changes in resource availability, are key issues in making this link.

The development of an approach for such an assessment is still in its early stages and like all aspects of the BBM, will no doubt be modified through further application and experience. Essentially, the overall objective of this chapter is to develop an ecological framework in support of a socio-environmental study that will:

- ensure that the social consultant collects data in a way that they can be used by the biophysical specialists;
- contribute to the development of a framework and guidelines for future studies of this nature.

Techniques described here may be familiar to social consultants, and their inclusion in no way serves to prescribe an approach or preclude an alternative. They are included simply because they have been found to be useful, and serve to help develop and describe an appropriate ecological framework. Participatory techniques, in particular, have the advantage of facilitating the collection of information from people who, in this case, may have extensive knowledge and wisdom concerning rivers, but for whom conventional interview techniques may be inappropriate.

9.3 OVERVIEW OF APPROACH

Current thinking within the arena of social impact assessments has shown that a questionnaire approach is frequently an inappropriate methodology (J. Stadler, Health Services Development Unit, University of the Witwatersrand, Johannesburg, pers. comm.). Disadvantages of non-participatory approaches include:

- raised and erroneous community expectations as to the products of the research, since such an approach does not provide the platform to clearly reiterate and revisit project objectives;
- the assumption that all interviewees equally understand new and complex issues;
- lack of full participation by communities, so that the collected data represent the views of a selected, and possibly inappropriate, group of individuals;
- data collection by non-interactive means, which does not allow for an explanation or exploration of new issues.

These disadvantages can be addressed by considering a range of approaches to the research. Adequate participation by the targeted communities can be achieved by careful consideration of the sociological approach, in terms of its inherent assumptions and constraints. It is recommended that standard participatory techniques, such as **Participatory Rural Appraisal** (PRA), be employed (Chambers 1983, 1992; Blackburn & Holland 1995; Nelson & Wright 1995). Additional interviews with key informants can be used throughout the process to clarify and add detail to issues. These techniques overcome many of the disadvantages and assumptions inherent in the standard questionnaire approach. To the newcomer, participatory methods may appear to be time consuming compared to using questionnaires. Whilst the initial time required to ensure collaboration between the researcher and the community groups is high, this investment is rewarded through the following advantages of participatory research.

- Once the process is in progress, large amounts of detailed information are collected in a short space of time.
- Data can be cross-checked through a process called triangulation, whereby participants monitor information given by others in a public forum. By contrast, respondents to questionnaires may give the answers that they think the interviewee requires if, for example, there are perceived benefits in doing so.

- Data validation is achieved through group work. This is in contrast to one-on-one interviews in the questionnaire approach, where the specialist must attempt to identify inconsistencies at a later stage without the interaction of the participants.
- It allows for sufficient participation and so should not fall foul of accusations by community members of lack of sufficient consultation.
- All interested community members can participate, including those who may be less vocal normally (such as women). Since all information can be presented visually, illiterate members of the group are not excluded.
- Sufficient time is allowed for trust and confidence to grow through interactions between the social consultant and the community and between community members. This interaction facilitates the development of a common understanding of the objectives of the work through a phased approach, and allows the consultant to clearly reiterate the objectives.
- The process of interaction with participants facilitates identification of new, or unresolved, issues that can be addressed immediately or at subsequent sessions. This usually cannot be achieved with questionnaires.
- The community is able to direct (to a certain extent) and ‘own’ the results of the research.

Given the objectives of the sociological appraisal, one of the most critical issues to be addressed by the social team is that the outputs of the research should facilitate the linkup of information to the overall objectives of the EFA. Not only should the types of data collected allow for interpretation by the biophysical specialists, but their format should also facilitate integration into the overall BBM assessment at a later stage. Thus, to capture information in a form that is useful to the biophysical specialists, data collection should be designed collaboratively. In doing so, issues such as the identification of plant material by a botanist, and the quantification of the relationship between resources and river flow, can be resolved prior to the research being undertaken. This information is required by the biophysical specialists because the flow regime (EFR) that is finally recommended will be designed, in part, to maintain valued river resources. These issues are dealt with in detail in Section 9.4.1.

The overall approach, summarised in Table 9.1, is intended to provide a framework that is sufficiently robust to allow tailoring to suit specific project needs.

Additional recommendations for how the process should be conducted include the following:

- workshop sessions should be conducted at the host villages and preferably at the river;
- where possible, the consultant should live on site, or close to it, during the appraisal;
- the consultant should be able to speak the local language, or at least one person who can speak it should be employed as scribe and facilitator;
- when possible, the relevant biophysical specialists, particularly the ecologists, should participate in the sessions in order to facilitate the identification of species and lead further key discussions where appropriate.

Finally, it should be noted that with participatory methods, much of the data analysis and presentation takes place on site, because each piece of information gathered is used in the subsequent session. This is reflected in Section 9.4.4, whilst collation of the final information is dealt with in Section 9.5.

Table 9.1 Overall process for assessing the human use of riverine resources.

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1. Explanation of research and general gathering of information from all participants
- Review project objectives and research approach with the participants.
- Identify what riverine resources are used.
- Identify who uses them.

2a. Focus group discussions (fish, medicinal plants, crafts, etc.)
- Prioritise the relative importance of each resource or use.
- Describe the location and extent of each resource.
- Ascertain the seasonality of use.

2b. Establishment of the link between the resource and flow
- Describe the critical water levels associated with each resource.
- Ascertain which seasons (and hence discharges) are important in terms of use or maintenance of the resource.
- Investigate how the resource may have changed with time and why.

3. Plenary session with all participants: summary of information gathered
- Collate the above information to develop an understanding of an acceptable Ecological Management Class.

9.4 SEQUENCE OF ACTIVITIES

9.4.1 Identification of potential communities and selection of study sites

The objective of this first activity is to identify all communities downstream of the development that could participate in the research, and to visit these communities in order to make a final choice of those to be involved. This work only proceeds after the study area has been delineated, and preferably once river sections and zones have been demarcated. It is carried out by the social consultant’s team, together with the appropriate biophysical specialists.

A desktop identification of all villages is followed by site visits to potential study villages. These may be selected based on their location within the study area (e.g. within river zones), their accessibility and possibly, their history of past participation in research. At the villages, discussions will be held with the appropriate community people or structures (e.g. the headman, the civic or the water committee), and their approval to carry out the appraisal will be sought.

The biophysical specialists, and particularly the botanist, consult with the social consultant to ensure that representative villages are selected in each river section. They also ensure that the BBM sites in each section represent the river resources being used by the corresponding villages. Together, they organise data collection so that all resource data are collected in a way that can be interpreted and integrated by the biophysical team. This includes, but is not confined to, ensuring that:

- all plants and animals used by the communities are named to species;
- the location of collected riparian plants are identified in terms of which inundation or vegetation zones they occupy;
- the hydraulic conditions commonly associated with valued aquatic plants (fast or slow flow, deep or shallow water, etc.) are known.

Villages that are potentially suitable for the assessment can be located on maps. The general aim is that, within logistical constraints, one or more target villages are chosen within each river section. Criteria for the choice of target villages are guided by the experience and local knowledge of the social consultant and may include those listed below.

- Size of the community. This will depend on the availability of time and money: a large village may provide more information, but require more workshops than a smaller one.
- Easy, direct access to the river and riverine resources.
- Established, strong social contact within that village.
- Length of time that the village has been established. If changes in river flow over time are of interest, village residents are likely to remember such changes.
- Distance from a chosen site. Including a community residing close to such a site allows participants to indicate water levels of importance to them at the surveyed cross-sections, facilitating the link between valued features and discharge.

In making initial contact with communities and inviting them to participate, the social consultant invests time in explaining the purpose of the work, with the aid of visual presentations. Presentations contextualise the research, with local examples of rivers that have been impacted by a development and hence why and how the government intends to address such issues. It is also critical at this point to stress that:

- the appraisal is **not** designed to address issues of domestic water supply;
- the provision of water for EFRs will not jeopardise or diminish the availability of water for domestic supply;
- information gained will be fed back to the community;
- the social consultant will attend the BBM Workshop in order to articulate community needs.

At this point, it is useful to allow people to briefly list the river resources that they use.

At the end of this activity, consensus should have been gained from the representative community structures on how to proceed with the appraisal. There should also be in-principle agreement by all sectors of the community (e.g. women and sangomas) to participate.

9.4.2 General identification of riverine resources used and of their location and extent

The social consultant and team carry out this activity at the chosen villages, to meet two objectives. Firstly, a general knowledge of resources used and their locations should be gained. This constitutes the basic data set of river use, providing an overview of all the riverine resources used by a community and who uses them. There are two categories of use:

- direct resource use (resources used directly from the river or riverine zone);
- use of the river for agricultural purposes (areas under cultivation, for example within the floodplain, and areas for grazing/watering of livestock).

Secondly, results from this survey should indicate the general use categories (e.g. fishing, cultural use, plants for crafts) that will be used to develop focus groups.

Data related to each resource should indicate whether or not the resource is instream or out of the water, its availability, its extent in terms of area and distribution and, if it is offstream, its distance from the river. A minimum data set would establish this for only the most important species.

Initially, a simple list is derived of resources used and who uses each of them. Thereafter, it is useful to introduce the theme of participatory information sharing, through an exercise such as mapping, so as to develop confidence within the group and to ensure participation by less vocal members. As a guide, participants may be asked to map their village, indicate who lives where and explain their relationships with the river. The exercise may also involve mapping social structures, classes, clans and so on, which can provide important context to understanding power relations within the village and control over resources. If such mapping is done at a sufficiently early stage of the survey, the consultant may be able to use it to assess the willingness or appropriateness of a certain village for inclusion in the study.

Having participated in mapping exercises, most participants have increased confidence about their knowledge and skills, and the survey proceeds to the drawing of resource utilisation maps. Such maps provide greater detail on the river and its surrounds, the resources used, and the distribution and extent of these resources (e.g. *Phragmites* reed beds, fishing grounds, agricultural fields, and so on). A minimum data set might comprise only a map of the resources with no validation of the extent of the resource.

The information provided should be checked by means of transect walks across the wider river channel, by the consultant and some community members. This allows for more accurate descriptions of the extent of the areas used, seasonal differences in the availability of the resource, the numbers of people relying on each resource, and general discussions regarding river water levels.

The results of the activity are presented with data from the third activity (Section 9.4.3).

9.4.3 Identification of resource users and of key focus groups

Whilst the above activity provides general information on the use of resources, it is important to then ascertain exactly who, and how many people, use a particular resource before prioritising the resources (Section 9.4.4). This can be achieved through questions to the group, or through a chart or table, and helps to identify key groups that can later be interviewed regarding that resource (e.g. women or sangomas). It may also indicate how widely used, and thus how socially and/or economically important, each resource is. This is particularly important in terms of judging the relative importance of the resource, for example, fish may be a major protein source for a large portion of the community or only mildly supplement the income of a few. The knowledge also serves to highlight areas of potential conflict around resource use.

Alternatively, the consultant may find a resource-use matrix useful, which involves not only listing who uses the resources, but also ranking resource importance in terms of use (Table 9.2). Additionally, this provides information for the following activity (Section 9.4.4). The matrix is not the key output, but simply a visual summary that allows for focused discussions. The content of these discussions is the most critical recorded output. This cautionary note applies to all the activities.

Table 9.2 Example of a total resource-use matrix. Asterisks denote an importance ranking on a scale of 1-5, with *** = very important and * = nominally important.**

	RESOURCE					
USER	A	B	C	D	E	F
Women	*****	**	*	*****	*	**
Children	*				*****	
Farmers	**				*****	
Sangomas	*****					*

As pointed out earlier, this activity highlights potential areas of conflict around resource use. For example, resource A is used by both women and farmers, but the activities of the farmer may compromise the resource for the women. Such a matrix focuses attention on common uses and generates discussion around apparent discrepancies or anomalies. The user groups then seek to resolve these by clarifying what arrangements they make to share access to the resource, such as use in different areas or at different times. Given these differences, this illustrates at this stage, how and why the desired future condition, or EMC, of the river may differ among groups within the community and confound later agreement. This should not be ignored, but rather confronted, with a view to addressing the differences and devising a mechanism for consensus.

9.4.4 Prioritisation of the relative importance of each resource or use within each use category

Once the resources and their users are known, the participants split into key focus groups associated with each use category, to complete an assessment of the relative importance of each resource. The appropriate composition of each group is critical, because different interest groups emphasise different priorities. In the assessment, it is valuable to distinguish between resources that are of primary, or supplementary, importance in terms of livelihood, thereby highlighting the key resources. This knowledge is used by the BBM team when setting a target EMC (Chapter 11) for the river. It is also used later in the process (Chapter 22) when, at Scenario Meetings, the communities are asked to indicate which of a range of possible future river conditions they would prefer.

For most use categories, this activity should be conducted at the river, so that plant and animal specimens or different “types” of water can be identified and/or collected. It is useful for the social team to have species lists and, where possible, drawings or photographs of the plants and animals likely to be associated with that part of the river, so as to facilitate field discussions.

There are three main steps in the field activity.

- **Collection and identification of the resources**. Different “types” of water (such as pools used for religious purposes) are indicated. Plant specimens and if possible animal specimens are collected, and the local names noted. Any relevant graphics or drawings done by the participants aid the exercise.
- **Listing of all resources, for use in the next step.** The list is checked with participants to ensure it is complete. Appropriate steps are taken (e.g. pressing and cataloguing plant samples) to ensure that, where appropriate, scientific names can be allocated to each resource.
- **Prioritisation of resources in terms of their relative value.** There are a number of ways this can be done. For instance, participants can each be asked to vote for their preferred resource (1 participant = 1 vote), according to perceived importance on the list produced in the previous step. Alternatively, they can jointly contribute to completing a prioritisation matrix (Table 9.3), with each participant making one entry. The resources are then simply ranked according to the number of entries made for them. This latter approach allows for discussion around the use of the resource and the extent of its use as a whole.

Table 9.3 Example of a resource-use prioritisation matrix. The number of + symbols indicates the number of participants ranking a resource as important.

	RESOURCE				
USE	A	B	C	D	E
Food	++++	+	+++	+	+
Income	+				+++++
Medicine	+++++			+++	

The matrix could alternatively be arranged to allow for pair-wise comparisons of each resource against the others, in order to illustrate relative importance (Table 9.4).

9.4.5 Seasonality of use

With the resources identified, the next step is to establish with the focus groups when each of the key resources is used. This provides the initial link with the river’s flow regime by including discussions on high and low flows. Within this activity the influence of climatic extremes, such as floods and drought, on the resource is also considered.

Developing a joint rainfall chart provides a useful initial orientation step at this stage (e.g. plotting rainfall over months, using bars of relevant heights to indicate rainfall), with some discussion around corresponding river flow. This allows for consensus on what constitutes "wet" and "dry" months, and how the river reflects these periods.

In terms of describing the seasonality of resource use, charts or tables can be used very effectively. For example, in an area such as KwaZulu-Natal with strongly seasonal rainfall, information could be allocated to wet and dry seasons. The list of resources used, together with rainfall and flow charts, can be used to develop a matrix of when these resources are used, as well as a description of why they are used at that time (Table 9.5). This is likely to produce links between resources and water levels, such as a certain riparian tree species that only fruits after much rain. The social consultant and biophysical team could subsequently ascertain if this phenomenon relates to a flood with a certain magnitude and return period.

Table 9.4 Example of a pair-wise ranking matrix to enable relative prioritisation and ranking of resources. Each resource is ranked relative to the others, and the number of these pair-wise comparisons scored by each resource is totalled. In this example, A scores 4, B scores 3, C scores 3, D scores 1, E scores 4 and F scores 0. These totals can be used for a final ranking of resources. Here, resources A and E both score the most comparisons but when ranked against each other, E is relatively more important.

	RESOURCES					
RESOURCES	**Species A**	**Species B**	**Species C**	**Species D**	**Species E**	**Species F**
Species A						
Species B	A					
Species C	A	B				
Species D	A	B	C			
Species E	E	E	C	E		
Species F	A	B	C	D	E	

To cater for differential use, and to aid cross-checking of information, it may be useful in this activity to divide the participants into groups such as men and women. This is because groups not involved in a specific activity may have different perceptions of when and how a resource is used than those that are involved. Groups can then be asked to present their findings to each other, and thereafter develop a joint matrix based on consensus. This serves to avoid any one participant or group under- or over-playing a certain resource use.

Table 9.5 Example of a resource-use and seasonality chart that can be developed for each use category.

RESOURCE	PURPOSE	WHEN USED	COMMENTS (linked to flow regime)
Fish		Dry months	Easy to catch in low water
Species A	Food		
Species B	Selling		
Plants			
Species A	Building material	Early wet season	Best to harvest after grown to full height after initial rains
Species B	Selling	Early wet season	As for species A
Species C	Fruit used for ceremonial purposes	End of wet season	Tree only bears fruit when rivers' water level reaches a certain height
Floodplain	Growing X type of vegetables	Planting in Y season Harvesting in Z season	X vegetable relies on initial flooding in spring

9.4.6 First link with flow: identification of general riverine water levels associated with each resource

This, and the following two activities (Sections 9.4.7 & 9.4.8), are designed to further investigate the relationship between the resources used and river flow.

This activity involves the social team and the key focus groups. At a later stage, it also involves the hydraulic modeller (Chapter 13) and the hydrologist (Chapter 12), who will link the water levels described to discharge magnitudes (hydraulic modeller) and return periods for the various size flow events (hydrologists).

There are a number of approaches that can be employed with the key focus groups to establish the link between the resource and river discharge. The most readily understandable currency for discharge, in this instance, is that of water levels. The crucial factor here is to introduce the concept linking flow with resource, for example, which resources are 'sensitive' to low or high flows or to changes in flows, and which require specific flows.

This can be achieved using a matrix of resources against various flow conditions, e.g. high and low flows. The sensitivity of resources to flow conditions would be indicated using input from participants, in the same way as for Table 9.3. Alternatively, Venn diagrams can be useful. Figure 9.1 illustrates the presence and quantity of specific resources with coded and different-sized circles. The relationships between resources and the relationships between resources and flow are indicated by the distance between circles (resources) and by their distance from the central box (flow condition).

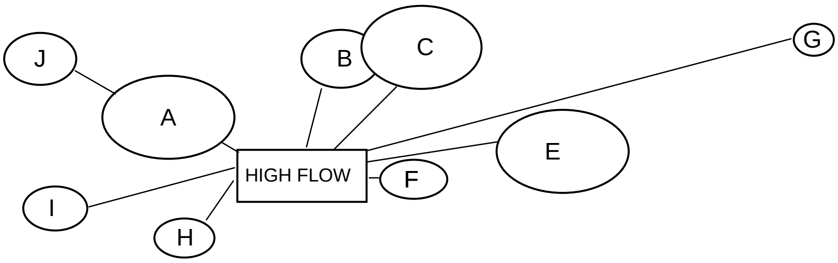


Figure 9.1 **Venn diagram representing the relationship of various resources to high flows. In this instance, resource F is not abundant (small circle) but very dependent on flow (close to central rectangle), whilst resource I, similar in abundance (small circle), is less dependent on flow (far from central rectangle).**

If this activity is conducted at one of the BBM sites, where there are established hydraulic cross-sections, participants can be asked to physically indicate levels along these, related to each resource used. These levels should be marked and made known to the hydraulic modeller so that they can be converted to discharge values. This might be possible through fixed-point photography, but discussion with the surveyor and hydraulic modeller is a vital first step. Other specialists who might need to be present at discussions concerning the water level are likely to be the fish biologist (where fish are caught) and the botanist (for vegetation zones), although any of the other specialists (see Chapters 12-19) may wish to make an input.

If the activity is not being conducted at a BBM site with surveyed cross-sections, a standard transect across the river should be agreed upon with the participants and used for specifying important water levels. Again, these levels should be permanently recorded, and the information from them discussed and quantified with the relevant biophysical specialists.

Presentation of the results is dealt with in Section 9.4.7.

9.4.7 Second link with flow: the quantity and seasonality of flow

With a general understanding gained of river flow levels linked to important resources, it is possible to obtain more details from the key focus groups on important flow attributes for each resource. This activity focuses on elucidating how the timing and magnitude of different kinds of low flows and floods might affect resources, and what other kinds of advantages and disadvantages could be related to different flows. Participants might indicate for example, that an initial small flood in early summer followed by increasingly larger floods later in the season is an important flow attribute for maintaining a resource, but floods that are too large or protracted may be deleterious. Again, the social team makes careful notes of all community discussions.

A seasonality diagram can be useful in that it allows the quantity of a resource to be plotted over an annual flow regime. This can be time consuming, however, and should be limited to key resources. The product of this activity could be a chart of resources versus flow attributes, where flow and abundance of resource are indicated visually for each month by, for example, bar lengths.

9.4.8 Third link with flow: past and present riverine conditions

In a final activity aimed at establishing the link between resources and flow, perceived changes of the river and its resources with time are investigated. The social team, working with the key focus groups and selected village elders, investigates if the perceived changes might be related to flow changes and if they have resulted in changes in the patterns of resource use. The advantages and disadvantages of any changes are discussed, as are the impacts of extreme (drought or flood) riverine conditions. It is important to attempt to set dates, or at least estimate roughly how long ago the described changes occurred.

To do this, the social consultant facilitates discussion around past and present conditions. Agreement among all participants is first sought on dates. This can be done by, for example, asking participants to link information on river change to some important event in the community that each participant remembers. Another approach could be to use (in this instance) an historical transect chart, in which years or decades are plotted against resources, indicating changes in abundance over time (Table 9.6). Alternatively, a chart could be created that ranks how abundant each resource is in drought years, in periods of 'normal' flow and in flood years.

Table 9.6 Historical chart of resource abundance to summarise changes over time and to generate discussion on possible reasons for these changes. Resource abundance is indicated by the number of '&' symbols, on a scale of 1-5.

DECADE	ABUNDANCE OF RESOURCE 'A'	ABUNDANCE OF RESOURCE 'B'	HISTORICAL EVENT TO HELP ORIENTATE PARTICIPANTS
1950s	&&&&&	&&&&&	
	&&		- Drought of 1952
1960s	&&&&&	&&	
	&&&		- Chief Mathebela died - Forestry started
1970s	&	&&&&	
			- Establishment of homeland in 1972
1980s	&	&&&&	
1990s		&	- Release of Mandela - Drought of 1992

Again, through discussion and indication at the channel transect, participants may wish to illustrate how flows have changed over the years and how they interpret concomitant resource changes. They may also discuss periods of drought and high rainfall separately. Finally, once changes have been described, they may be able to suggest potential, or perceived, reasons for these changes, such as changes that may have been noted in relation to the construction of a dam.

At a later stage, any described changes in both flow regime and resources should be linked to historical flow records where possible.

9.4.9 Determination of the Desired State of the river

In order for the social consultant to be able to adequately represent the communities in all further stages of the BBM, it is necessary to establish some consensus among all the participants in previous activities on a condition or DS for the river. Care should be taken not to create the impression that the people can have whatever kind of flows they want. Discussions should rather focus on the importance of the various resources used, their links to flow attributes, and which of these resources it is most important to maintain in the future.

Essentially, this involves a ‘mini-BBM’ approach with the communities, in which blocks of flow are identified and some sort of flow regime defined. An annual time line is a useful tool, enabling desired ranges of flow to be identified for each month with the main reasons. It may be useful to have participants summarise findings per key focus group and then present these to other groups in a final plenary session. This also serves to provide the final quality check on information.

9.4.10 Collation and cross-checking of information with the Building Block Methodology specialist team

Before the data from the above activities are presented at the BBM Workshop, the information is checked with relevant biophysical specialists on the team. This ensures that there is general agreement between the data provided by community participants and scientific information available from the other specialist groups. This may highlight areas where there is conflicting information, such as the incorrect identification of species, requiring re-checking with the appropriate community participants. All social perceptions of river ecosystem functioning, such as floods that are thought important for the breeding of a certain fish species, are checked with the specialists to ensure that there is consistency in the information used.

To facilitate the check, the resources used can be listed, together with comments regarding the flow requirements associated with each resource. Relevant specialists should then study this list for anomalies. In all cases where social information appears to conflict with available specialist data, the reasons should be sought and a final decision taken on how to use the social data.

9.5 MINIMUM AND IDEAL DATA SETS

Comments on this topic have been included at points through Section 9.4. In general, for minimum data sets, details provided by the activities described in Sections 9.4.4-9.4.8 are limited to those concerning species or activities rated as most important by the community. Ideal data sets, on the other hand, include as comprehensive a list as possible. In terms of the activities in Sections 9.4.6-9.4.8, an ideal data set would be produced if these aspects were addressed at the BBM sites, where surveyed cross-sections are in place. However, logistical constraints may preclude this.

9.6 STARTER DOCUMENTATION FOR THE WORKSHOP

- Introduction.
- Terms of Reference.
- Objectives and key questions.
- Study area.
- Approach taken.
- Results.
    - General.
    - Focus group data. These may be drawn from groups dealing with religious or cultural issues; fishing; plants; etc. Each set of data should include:
        - a general description of resources used by that group;
        - location and extent of each resource;
        - prioritisation of resources;
        - main users of each resource;
        - seasonal availability of each resource;
        - relationship between flow and availability of each resource;
        - perceived long-term changes in availability of each resource.
- Desired future condition of the river.
- Discussion and conclusions.
- References.

9.7 ROLES AND RESPONSIBILITIES AT THE WORKSHOP

The role of the social consultant is to articulate, on behalf of the communities, the use of riverine resources by rural communities. Additionally, information on a desired future condition is fed into discussions on the selection of an EMC, which take place before the BBM Workshop (Chapter 11).

At the workshop, it is the responsibility of the social consultant to describe past problems, future needs and potential areas of conflict regarding river resources. The validity of extrapolating results to other areas/communities along the study river should also be explained.

In essence, the social component is an integrator of other aspects of the BBM in that it includes information on both abiotic and biotic aspects of the system. In this regard, a further responsibility includes final cross-checking of social information with that of the other specialists (see Section 9.4.10).

9.8 ROLES AND RESPONSIBILITIES AFTER THE WORKSHOP

A major responsibility of the social consultant is to ensure that the results of the workshop are fed back to the participants involved in the research.

Furthermore, following the workshop, any later Scenario Meetings should be used to present to the communities the various options of what the river could be like in the future (see Section 9.11).

9.9 EXAMPLE OF TERMS OF REFERENCE

The social consultant should achieve the following tasks.

- Understand the concepts and principles of the BBM and design a study to facilitate their application.
- Know the extent of the study area and achieve the following research objectives:
  - describe the type, diversity, extent and seasonality of instream and riparian resources that are used by rural communities of the river in question and further, describe the user groups;
  - estimate, together with the user groups and the community as a whole, the relative importance of resources to the local communities in question;
  - link the availability of the resources to the discharge of the river;
  - determine how the availability of these resources has changed over time and further, if these changes can be linked to changes in the flow regime;
  - determine the problem issues relating to the river that have been experienced over the last decade or so;
  - from the above data determine, with the community, what would be acceptable future conditions of the river.
- Use participatory methodologies or, if an alternative approach is used, justify this and ensure that it is agreeable to the main consultant.
- Collect data in such a way that the necessary links with other appropriate specialists on the BBM team can be made. This will involve initial consultation with these specialists prior to undertaking the project, and their inclusion in the fieldwork where possible.
- Collate and cross-check data with the specialist team.
- Write a report of the study findings and present the output of the research at the BBM Workshop.
- Ensure that research results and outputs of the workshop are fed back to the communities.

9.10 MINIMUM AND OPTIMUM SPECIALIST TRAINING

As a minimum requirement, both the social consultant and team should have training and experience in community work, and specifically in the use of participatory research methods. The quality of information gathered will be greatly enhanced if the social consultant has some previous knowledge and experience of research in the field of natural resource utilisation, and if he/she collaborates with a river ecologist and a hydrologist.

9.11 POTENTIAL PITFALLS

Issues regarding the use of river resources are complicated and require a clear understanding on the parts of both the community and the social consultant. Clear preparation on the part of the research team could pre-empt many potential problems. A primary problem that may arise is that of raising expectations, which is a reality of any work with communities, particularly poor rural peoples. Techniques and interactions need to be developed that allow for a clear, common understanding of what the research is about. This understanding is dependent on clearly stating the objectives of the research and on adopting a methodology that allows sufficient time for interaction. More importantly, participatory techniques should be enjoyable, as enjoyment of the procedure is an important component in gaining quality information. Furthermore, many of the original and transcribed products of the PRA methodology, such as maps and charts, can be returned to the communities in feedback sessions.

The issue of the availability of ecological expertise throughout the research has already been raised. The danger of excluding such expertise is that the large quantities of information given during the activities cannot be verified at each step. Where anomalies are identified later, it may be extremely difficult to return to the community and consult the original group of participants. Thus it may be a false economy to exclude an ecologist from the social team, as the reduction in costs may be countered by a loss in the quality of the data.

Since a large quantity of complex information is collected fairly intensively, a further potential pitfall is that of ‘workshop fatigue’, which could result in valuable participants leaving. The consultant should be aware of this, and prepare adequately to make the workshop as simple and visual as possible.

Finally, as in all research, a major constraint is that of finance. This is a serious constraint in social research because the consultant relies entirely on information from community members. If funds are inadequate, workshops tend to be rushed and hence confused, calling into question the quality of data collected.

9.12 FURTHER DEVELOPMENTS

9.12.1 Quantification of the resource base and resources used

Effectively, the social assessment outlined above provides a rapid, qualitative baseline appraisal of the riverine resources that are available and used by communities. This information is an input to the development of an EMC (Chapter 11).

A more comprehensive assessment would include quantitative data on both the resource base and the resources used. Such information greatly enhances the quality of ensuing monitoring programmes (Section 9.13), as the objectives to be achieved are defined in measurable terms. Given the speed and ubiquitous nature of water-resource developments in southern Africa, this detail is beyond the remit of most EFAs currently being done, although the EFA for the Lesotho Highlands Water Project did provide such quantitative data (Metsi Consultants 2000a).

Improved methods that address such concerns should constantly be striven for in future work. If the social and biophysical teams are given sufficient lead-in time, the outlined social assessment lends itself to the incorporation of empirical methodologies that would allow for both quantification of the resource base and of the amount of resources used, even if only for one season. Such information would not only provide better input into the deliberations on the EMC and the monitoring programme, but also allow the economic impacts of environmental change to be costed for subsistence communities (see below).

9.12.2 Assessing the full social impact of flow manipulations on communities

Flow-related changes in river condition impact on the quality of life of rural communities. Many river resources are used by them for sustenance, or sold for income. The real impact of losing these riparian resources is still largely unrecorded and poorly understood, although quantitative information on the use, and loss, of terrestrial resources indicates that the social and economic impacts may be high (e.g. McGregor 1995; Shackleton & Shackleton 1997; Pollard *et al.*, 1998; High & Shackleton 2000). Notably, most of the social research efforts directed at rural communities have been orientated towards indigenous woodlands; few towards instream resources such as fisheries, or wetlands, and to the author’s knowledge, almost none have focused specifically on the riparian zone (but see Metsi Consultants 2000a). Thus, with much of the information extrapolated from studies that are far wider than the river itself, spatial refinement of these data would furnish the BBM process with a more accurate assessment.

Decisions on water-resource developments made without this knowledge may be biased, or may trivialise, or ignore, the expected impacts on riparian communities. As a result of their vulnerability, ascertaining the socioeconomic value of the river resources they use should be part of any EFAs. Only then can the full cost of a water development to be understood. Such an EFA would require linking and integrating a number of key components, including the health-related, and economic, impacts of changes in the resource base to peoples’ livelihoods, as well as changes in the social dynamics within communities as a result of changes in access to resources (Section 9.13). Currently, approaches for assessing the economic value of the environmental resources used, under the broad discipline of resource valuation, are available and should be incorporated into the BBM. Further development is required of methods to ascertain how river changes described by biophysical specialists will affect both the health and livelihoods of riparian communities in the longer term. The BBM would need some adaptation to incorporate such a predictive capacity, similar to that encompassed in DRIFT (Section 3.5.2; Brown & King 1999).

9.12.3 Collective community assessment of the desired condition of the river

One of the major challenges for the social team is to facilitate a description of the desired condition (DS) for the river, which integrates all the information provided by participants throughout the research. Previous studies have revealed that participants find it difficult to produce a single or collective interpretation for all user groups of the benefits and drawbacks of a flow regime, and even less so of a number of potential flow regimes. This has been particularly difficult in sensitive cases where one benefit appears to undermine, or preclude, the needs of another user group. Such constraints are likely to be further exacerbated by unstated community dynamics and power relations, where predicted benefits would accrue to only a few powerful individuals within the community.

Participants would be more able to indicate the impact of potential changes in river condition on their lives if a scenario-based approach was used. This would provide a range of possible future river conditions, each linked to a specific modified flow regime, as is done in DRIFT (Section 3.5.2), which would enable rural communities to participate more constructively in discussions on acceptable river conditions. Developing and incorporating this as a formal step within the BBM would enhance the final outputs of the social assessment.

9.13 MONITORING

A key step in any comprehensive EFA is that of monitoring the efficacy of the chosen flow regime. It is not the purpose of monitoring programmes to predict all possible future changes, but to identify key changes and their causes.

An effective monitoring programme should integrate biophysical and social aspects, and provide quantified data where possible on:

- changes in resource base;
- changing patterns in resource use;
- the social and economic consequences of these.

Important issues to consider in designing this programme are as follows.

Changes in the resource base

Key resources identified during the baseline social assessment should be tracked by the biophysical team. For instance, if the variability of flow is reduced, it is likely that riparian vegetation zones will diminish in size. The result in terms of abundance of key species or other resources, and their use, should be recorded.

Changing patterns in resource use

Monitoring programmes should be designed to distinguish changes in resource use that are related to flow from other causes. For instance, reduction in the use of a medicinal plant may reflect a number of causes. It could be due to a decreased abundance of that species because of modifications to the flow regime, or to a coincidental health intervention that provided people with a new source of medicine.

The programme should also facilitate assessment of whether changes in resources are as predicted, who is most affected, and whether compensation or mitigation measures are needed.

The social and economic consequences of changing patterns in resource use

Methods need to be developed by social specialists to formalise the use of biophysical predictions of river change for prediction of the ensuing social consequences. At present, any quantitative biophysical predictions made are likely to then be interpreted by the social team using expert opinion.

Current thinking within the arena of natural resource use and management tends to accentuate the importance of quantifying the economic value of the natural assets of a project area. By implication, quantifying the economic value of resources lost through flow changes thus provides sufficient means by which to gauge the socioeconomic consequences of changes in river resources. However, resource economics is but one component of a broader spectrum of relevant issues. It is recommended that three key issues, amongst others, should inform the design of a monitoring programme for tracking social implications of flow changes. These are: health-related impacts; economic impacts; and changes in the social dynamics of communities through changes in access to resources.

Important questions can guide this monitoring. Firstly, how important are river resources as a nutritional source? What are the present levels of health of the riparian people and their domestic stock, and how might this change with flow change? Clinics and other health services or studies in the area could provide invaluable historical information. For instance, the general health records for the area provide an assessment of current disease levels, and any future changes in water-related illnesses of riparian communities could be compared with these. Secondly, in economic terms, have peoples' livelihoods improved, or declined, as a consequence of flow changes?

A total economic valuation, accounting for both the use and non-use values of the riverine ecosystem would provide the most comprehensive assessment. Even within a more focused study, the value of the goods used in terms of cost saving (replacement costs), or as additional household income through goods traded, requires consideration, and appropriate expertise in this field should be sought prior to undertaking such work. Finally, it is important to address changing social dynamics in the communities resulting from improved or reduced access to certain resources. Tensions regarding the benefits accruing to certain individuals, or groups, within the community will undoubtedly influence peoples' perceptions with regard to perceived impacts of altered flow regimes. For example, the perceptions of influential non-users around monetary compensation might distort the real impacts of the altered flow regime. It is critical that these types of issues are tracked in the monitoring phase.

9.14 CONCLUSIONS

If meaningful data are to be collected for the social assessment component of an application of the BBM, a participatory methodology is recommended. This overcomes many of the constraints of a more conventional approach, where there is a very real danger that the issues raised by the social consultant will remain abstract. The methodology described here provides a number of steps, and suitable tools with which to address each step. It is hoped that this will serve as a useful guide and source of ideas for the social team. There are, however, a wide range of tools available within participatory techniques and many different ways of achieving the desired result.

The overall approach is designed to provide a qualitative assessment of the impacts of changes in flow on the lives of rural communities, but could be usefully expanded to include quantitative methods. With sufficient preparation and integration with the biophysical team, both the resource availability and use can be quantified. Useful refinements to the methodology would be further development of methods to provide information on the impacts of changes in flow regimes on the health, socioeconomic profiles and social dynamics of the affected communities.

Finally, the process of developing a monitoring programme should be iterative. Additional inputs and findings will improve our current understanding of the livelihood needs of riparian people, and the relationship between livelihood security and natural resources.

10. ASSESSMENT OF ECOLOGICAL IMPORTANCE AND SENSITIVITY

Neels Kleynhans and Jay O'Keeffe

10.1 DEFINING ECOLOGICAL IMPORTANCE AND SENSITIVITY

The ecological importance of a river is an expression of its importance to the maintenance of ecological diversity and functioning on local and wider scales. Ecological sensitivity (or fragility) refers to the system's ability to resist disturbance, and its resilience or capability to recover from disturbance once this has occurred (Resh *et al*., 1988; Milner 1994). Both abiotic and biotic components of the system are taken into consideration in the assessment of ecological importance and sensitivity.

The assessment presented in this chapter is a general and unrefined estimation. It is strongly biased towards the potential ecological importance and sensitivity of the particular river section under consideration as that would be expected to be under unimpaired conditions. This means that the PES or condition is generally not directly considered in determining ecological importance and sensitivity. However, in the assessment of the present ecological (biological and habitat) integrity, the reality of what is currently present and the condition that is attainable, is taken into account and used to enhance the realism of the estimation.

10.2 ECOLOGICAL IMPORTANCE AND SENSITIVITY IN THE BUILDING BLOCK METHODOLOGY

Assessment of ecological importance and sensitivity comes at an early stage in the BBM, and is a vital part of the process for deciding on a future EMC (Chapter 11) and of setting ecological objectives for the river. The process of setting objectives can be expressed as a set of questions, which are summarised in Section 4.4 & Table 4.2. One of the questions concerns the ecological importance and sensitivity rating. The answer has a major influence on the final decision of whether to set the EMC at the same class as the present state, or higher. For example, a river presently in a C class, and with a low importance rating, would probably be rated as having an EMC of C. However, a river presently in a C class, but with a high importance rating (e.g. because of the presence of rare and endangered species), would probably require an improved EMC of B if this is still attainable.

10.3 ASSESSING ECOLOGICAL IMPORTANCE AND SENSITIVITY

The Kleynhans Model currently used, estimates and classifies the ecological importance and sensitivity of the river or river section, by considering a number of components surmised to be indicative of these characteristics (Kleynhans 1999a). It is advisable to classify the river section under consideration according to an ecological typing framework, in order to enhance the ecological sensitivity and reality of the approach.

The following ecological aspects are the basis for the assessment.

- For both instream and riparian components of the river: the overall species diversity, and the presence of rare and endangered species, unique species (i.e. endemic or isolated populations) and communities, and species intolerant of change.
- Reaches with a high diversity of habitat types such as pools, riffles, runs, rapids, waterfalls and riparian forests.
- Biodiversity in its general form (i.e. *sensu* Noss 1990), as far as available information allows inclusion of this aspect.
- Importance of the river or stretch of river in providing connectivity between different parts of the system, that is, whether it provides an important migration route or corridor for species' movements.
- The presence of conservation or other relatively natural areas along the river section.
- The sensitivity (or fragility) and resilience of the system. Biotic and abiotic components of the river should be considered.

This model guides the deliberations of professional ecologists who should be familiar with the area. The assessors score a number of biotic and habitat determinants (Section 10.3.1.) considered important for the determination of ecological importance and sensitivity. The median of these scores provides a rating of ecological importance and sensitivity on a four-point scale of classes (Table 10.1).

Table 10.1 Ecological Importance and Sensitivity Classes.

CLASSES	GENERAL DESCRIPTION
Very high	Rivers that are unique on a national or even international level in terms of biodiversity aspects (habitat diversity, species diversity, unique species, rare and endangered species)
High	Rivers that are unique on a national scale in terms of biodiversity aspects
Moderate	Rivers that are unique on a provincial or local scale in terms of biodiversity aspects
Low/marginal	Rivers that are not unique at any scale

10.3.1 Determinants

A four-point (1-4) or five-point (0-4) scoring system is used to assess the various aspects of ecological importance and sensitivity. Determinants either address biological characteristics (Table 10.2) or aquatic habitat (Table 10.3). Some determinants are treated differently for the Western Cape, South Africa, because of the uniqueness of the Fynbos Biome.

10.3.2 Determining the Ecological Importance and Sensitivity Class

In determining the Ecological Importance and Sensitivity Class (EISC), no weighting of the relative importance of the various components of ecological importance and sensitivity is proposed at this stage. However, it is required that the relative confidence of each rating be estimated based on a scale of four categories (Table 10.4). The possibility of using confidence ratings as indicators of the relative weights of various determinants is currently receiving attention.

The median score for the biotic and habitat determinants is interpreted as indicated in Table 10.5.

10.4 MINIMUM AND IDEAL DATA SETS

The above approach can be used at differing levels of confidence according to the level of information available. As a minimum, there is a requirement for some information on the presence of rare, endangered or unique species in the river (principally vertebrates, but including riparian plants and aquatic invertebrates). There should also be sufficient information to make at least an approximate evaluation of the biodiversity of the system, and to estimate the sensitivity (or fragility) of the biotic and abiotic components of the system. An estimate is also required of habitat diversity, the importance of the study area as a migration route, and the presence of conserved areas within or adjacent to the study area.

Ideally, the process requires a complete inventory of the biota of the river in its natural state, a geomorphological analysis, and an assessment of biodiversity in terms of the criteria of Noss (1990). Also required is knowledge of the relative sensitivity of different species and lifestages to a range of flow-related disturbances. In practice, such a wealth of knowledge is seldom available, and the scoring system is relatively coarse, acknowledging that it is more important to capture the essence of the river rather than its details. The test of the model is whether it produces a result that conforms to the expectations of a specialist with experience of the studied river. The model therefore aims to provide a consistent method of capturing specialist knowledge, rather than to calculate an exact numerical description of ecological importance and sensitivity.

10.5 STARTER DOCUMENTATION FOR THE WORKSHOP

The specialist responsible for the assessment will need access to the information and expertise of the other specialists. For this reason, the assessment is usually undertaken at the BBM Workshop. However, if the information is available beforehand, the assessment can be made prior to the workshop, and a chapter for the starter document produced. In this case the chapter should provide one or two tables indicating the ratings for each determinant (as listed in Tables 10.2 & 10.3), and the resulting median score and interpretation (as per Table 10.5). There should follow an expansion of the reasons for the allocation of each score for each determinant, with an associated confidence rating (as per Table 10.4). The first author of this chapter has a spreadsheet version of the model which provides a summary output of the process.

If the assessment is undertaken prior to the workshop, the other specialists should be provided with the results, to ensure that there is consensus regarding the importance and sensitivity rating.

10.6 EXAMPLE OF TERMS OF REFERENCE

The Terms of Reference for an assessment of the ecological importance and sensitivity should be:

- to gather the information required for rating the determinants according to the Kleynhans Model (Kleynhans 1999a);
- to apply the Kleynhans Model;
- to check with each of the relevant specialists that (a) the input to the relevant determinants is correct, and (b) the resulting score is reasonable in their opinion;
- either to produce a report describing and motivating the results, as part of the starter document for the BBM Workshop, or to facilitate a group discussion and assessment, using the Kleynhans Model, at the workshop.

10.7 MINIMUM AND OPTIMUM SPECIALIST TRAINING

Ideally, the specialist responsible for the assessment of ecological importance and sensitivity should be one of the ecological specialists working on the BBM project, and should have extensive personal experience of the study river. This is not essential, however, as long as the score for each determinant is checked with the relevant specialist, the final results are checked with the BBM team, and consensus on the overall rating is reached with these specialists. The person responsible should have a clear knowledge of how the Kleynhans Model works, and how the results are used in setting the EMC and ecological objectives.

Table 10.2 Biotic determinants, instream and riparian, for assessment of ecological importance and sensitivity.

DETERMINANT	GUIDELINES AND DESCRIPTION [#]	SCORING GUIDELINES *
Rare and [@] endangered biota	Biota can be rare or endangered on a local, Provincial or National scale. Useful sources for this information include the South African Red Data Books that are suitable for assessment on a National scale.	• Very High (Rated 4). One or more species/taxa rare or endangered on a National scale. • High (3). One or more species/taxa rare or endangered on a Provincial/regional scale. • Moderate (2). More than one species/taxon rare or endangered on a local scale. • Marginal (1). One species/taxon rare or endangered at a local scale. • None (0). No rare or endangered species/taxon at any scale.
Unique biota [@]	Include endemic or uniquely isolated species populations (or taxa, i.e. in the case of invertebrates) that are not rare or endangered. Do not include rare and endangered species assessed in the previous category. The assessment should be based on professional knowledge. The Fynbos Biome in the Western Cape is a hotspot of biodiversity with many endemic species. This region is thus assessed separately.	• Very High (4). One or more populations (or taxa) unique on a National scale. For the Western Cape, rate at the Biome scale. • High (3). One or more populations (or taxa) unique on a Provincial/regional scale. For the Western Cape, rate at a sub-regional scale (i.e. northern, western, southern and karroid). • Moderate (2). More than one population (or taxon) unique on a local scale. • Marginal (1). One population (or taxon) unique at a local scale. • None (0). No population (or taxon) unique at any scale.
Intolerant biota	Intolerant taxa include those that are known (or suspected) of being intolerant to decreased or increased flow conditions, as well as to flow-related changes in physical habitat and water quality. As little experimental information is available on the intolerance of indigenous biota, assessment should be based on professional judgement. Where all rivers are perennial (and would thus score highly), use fish only.	• Very High (4). A very high proportion of the biota dependent on permanently flowing water during all phases of life cycles. • High (3). A high proportion of the biota dependent on permanently flowing water during all phases of life cycles. • Moderate (2). A small proportion of the biota dependent on permanently flowing water during some phases of life cycles. • Marginal (1). A very low proportion of the biota temporarily dependent on flowing water for the completion of life cycles. Sporadic and seasonal flow events expected to meet needs. • None (0). Few if any biota with any dependence on flowing water.
Species/taxon richness	This kind of assessment should be based on the grouping of ecologically similar rivers. However, such a system is still under development, and so at present should be based on professional judgement.	• Very High (4). Rated on a National scale, except for the Western Cape where it is rated on a Biome scale. • High (3). Rated on a Provincial or regional scale, except for the Western Cape where it is rated on a sub-regional scale (i.e. northern, western, southern and karroid). • Moderate (2). Rated on a local scale. • Marginal/low (1). Not significant at any scale. • A rating of none is not appropriate in this context.

The current guidelines are mostly applicable to vertebrates and vascular plants, for which groups information is more readily available. In cases where expert knowledge allows for the assessment of biota other than these groups, such information should be included. The taxonomic groups on which the assessment is based should be indicated. In cases where invertebrates (in particular) and other plants are used as indicators, the scoring system may have to be adapted by the relevant ecological experts.

[@] In the case of rare and endangered, or unique, biota, the highest of the possible scores should be provided.

* If a species is rare and endangered on a national scale, it should be scored as very high.

* If a species is rare and endangered on a regional scale but unique on a national scale, it should be scored as very high.

Table 10.3 Determinants for instream and riparian habitat, for assessment of ecological importance and sensitivity.

DETERMINANT	GUIDELINES AND DESCRIPTION	SCORING GUIDELINES *
Diversity of aquatic habitat types or features	Assess at local, Provincial and National scales. Habitats include riffles, rapids, runs, pools and backwaters and the associated marginal areas and substratum types; and lotic wetlands, including source sponges, floodplain habitat types and the riparian zone. Assessment based on professional judgement.	• Very High (4). Rated on a National scale. • High (3). Rated on a Provincial/regional scale. • Moderate (2). Rated on a local scale. • Marginal/low (1). Not significant at any scale. • A rating of none is not appropriate in this context.
Refuge value of habitat types	Assess the functionality of the habitat types present in terms of their ability to provide refugia to biota during periods of environmental stress. Based on available information and expert judgement.	• Very High (4). Rated on a National scale. • High (3). Rated on a Provincial/regional scale. • Moderate (2). Rated on a local scale. • Marginal/low (1). Not significant at any scale. • A rating of none is not appropriate in this context.
Sensitivity of habitat to flow changes	Take into account the size of the river/stream as well as the habitat types available. A limited decrease or increase in the discharge, depth and wetted width of some rivers/streams could result in specific habitat types (e.g. riffles), becoming unsuitable for biota. Based on available information and expert judgement.	• Very High (4). Rivers/streams with abundant flow-sensitive habitat types. • High (3). Rivers/streams with some flow-sensitive habitat types. • Moderate (2). Rivers/streams with some flow-sensitive habitat types that are susceptible at certain seasons. • Marginal/low (1). Rivers/streams with few flow-sensitive habitat types. • A rating of none is not appropriate in this context.
Sensitivity to flow-related water quality changes	Consider the size and flow of the river/stream in terms of its sensitivity to water quality changes. A change in the natural discharge may, for example, result in a diminished assimilative capacity for effluents, or water quality variables such as water temperature and oxygen reaching levels detrimental to the biota. Smaller streams may be more vulnerable due to lower discharges. In terms of organic pollution load, slow-flowing deep rivers may be impacted over greater distances than fast-flowing shallow rivers that would have higher reaeration rates (Chutter 1999). Assessment is based on available information and expert judgement.	• Very High (4). Usually small streams with abundant habitat types that are highly sensitive to flow-related water quality changes. • High (3). Usually small streams with some habitat types that are highly sensitive to flow-related water quality changes. • Moderate (2). Often larger rivers with some habitat types that are sensitive to flow-related water quality changes. • Marginal/low (1). Often larger rivers with few habitat types that are sensitive to flow-related water quality changes. • A rating of none is not appropriate in this context.
Migration route/corridor for instream and riparian biota	Assess the importance of the upstream/downstream connectivity provided by the river/stream. Based on professional judgment and available information. Sensitivity of the migration route/corridor to modifications and disruptions forms part of the assessment. Within this context, headwater rivers would mostly have a low importance as a migration route/corridor.	• Very high (4). The river/stream is a critical link in terms of connectivity for the survival of upstream and downstream biotas, and is very sensitive to modification. • High (3). The river/stream is an important link in terms of connectivity for the survival of upstream and downstream biotas, and is sensitive to modification. • Moderate (2). The river/stream is a moderately important link in terms of connectivity for the survival of upstream and downstream biotas, and is moderately sensitive to modification. • Marginal/Low (1). The river/stream is a marginally/little important link in terms of connectivity for the survival of upstream and downstream biotas, and has a marginal sensitivity to modification. • None (0). The river/stream is not important in terms of connectivity for the survival of upstream and downstream biotas.

/…Continued

Table 10.3 Continued.

DETERMINANT	GUIDELINES AND DESCRIPTION	SCORING GUIDELINES *
National parks, Wilderness areas, Nature reserves, Natural Heritage sites, and natural areas	The presence of conservation and relatively natural areas within a study river/stream places an additional emphasis on its ecological importance and sensitivity. The importance of such areas for the conservation of aquatic ecological diversity at different scales must be judged. The location of a river/stream in a conservation or natural area does not automatically warrant a high score.	• Very high (4). The river/stream is present within an area very important for the conservation of ecological diversity on a National and even international scale. • High (3). The river/stream is present within an area important for the conservation of ecological diversity on a National scale. • Moderate (2). The river/stream is present within an area important for the conservation of ecological diversity on a provincial /regional scale. • Marginal/Low (1). The river/stream is present within an area important for the conservation of ecological diversity on a local scale. • Very low (0). The river/stream is not present within an area important for the conservation of ecological diversity at any scale.

* The scoring system is mainly applicable to vertebrates. In cases where invertebrates in particular, and plants, are used as indicators, the scoring system may have to be adapted by the relevant experts.

Table 10.4 Confidence ratings for biotic and habitat determinants.

CONFIDENCE RATING	CONFIDENCE SCORE
Very high confidence	4
High confidence	3
Moderate confidence	2
Marginal/Low confidence	1

Table 10.5 Ecological Importance and Sensitivity Classes: interpretation of median scores for biotic and habitat determinants.

ECOLOGICAL IMPORTANCE AND SENSITIVITY CLASS	RANGE OF MEDIAN
Very high Rivers that are unique on a national or even international level based on biodiversity aspects.	> 3 and ≤ 4
High Rivers that are unique on a national scale based on biodiversity aspects.	> 2 and ≤ 3
Moderate Rivers that are unique on a provincial or local scale based on biodiversity aspects.	> 1 and ≤ 2
Low/marginal Rivers that are not unique at any scale.	> 0 and ≤ 1

10.8 POTENTIAL PITFALLS

The assessment model (Kleynhans 1999a) is based very much on the assumption that rarity, endemism and diversity are the key attributes for establishing the importance of a river system, and that these should influence the process of setting ecological goals for the river. There are cases of rivers, especially ones in the C-F PES classes, for which the objectives may be much more people-use oriented. For example, where there is a subsistence fishery, this will usually be exploiting very common species, which will have a low score in the Kleynhans Model. The ecological importance of such socially important components of the ecology will not be adequately reflected in the model. A similar model designed to reflect the social dependence on a healthy riverine ecosystem is at a prototype stage (Huggins & O'Keeffe 1999), but has yet to be extensively used. There are also plans for an economic version of the importance model (DWAF 1999a), but it is unclear how the results of the various models might be used interactively to influence assignment of the EMC.

11. ECOLOGICAL MANAGEMENT CLASSES

Jay O'Keeffe and Delana Louw

11.1 OVERVIEW OF THE ECOLOGICAL MANAGEMENT CLASS

The concept of the EMC was introduced in Section 4.5, and is described in detail in DWAF (1999b). Briefly, the South African Water Act requires that water resources are classified, and the EMC system has been developed by DWAF task teams to guide this process. EMCs provide a generic description of the ecological management target for a water resource, expressed as classes A-D, where A represents virtually unmodified, natural conditions (usually the Reference Conditions), and D represents a high degree of modification from natural conditions. Two additional classes, E and F, may describe the present ecological state of the river, but represent a high degree of modification from the natural state and are thus not used to describe the EMC (Section 4.5). Table 11.1 lists, for each class, the descriptors for major components of the riverine ecosystem.

The BBM specialists make recommendations regarding EMCs, based on the data gathered during the study. They may also predict the consequences of adopting a particular EMC. The stakeholders also recommend one or more acceptable EMCs, with the Minister of Water Affairs and Forestry taking the final decision on which EMC is set for any river.

The EMC for a particular water resource is set after consideration of the PES class (classes A-F), the ecological importance and sensitivity of the resource (Chapter 10), the social importance (Chapter 9) and any potential improvements in resource quality. It should be noted, however, that "some prior impacts or modifications may not be practically reversible due to technical, social or economic constraints"

(DWAF 1999b). The EMC may be set at the same level as the PES, or at a higher class, but may not normally be set lower than the present state, since this would represent a long-term objective to degrade the resource. Once the EMC is set, it becomes the overall management target for the long-term protection and management of that ecosystem. The flow recommendations made using the BBM will then be designed to maintain or achieve the EMC. As the EMC is a generic target, specific measurable objectives then have to be set within it. For example, in the sections of the Sabie River for which an EMC of B was recommended, objectives included (Tharme 1997c):

- slowing down or reversing the process of reed encroachment;
- generation and establishment of riparian seedlings;
- maintenance of riffle habitat for the indicator species, the pennant-tailed rock catlet (*Chiloglanis anoterus).*

With these specific objectives in place, monthly flow recommendations to facilitate their achievement were defined.

Table 11.1 Descriptions of each of the Ecological Management Classes (from DWAF 1999b). TWQR - Target Water Quality Range; SASS - South African Scoring System; CEV - Chronic Effects Value; AEV - Acute Effects Value.

CLASS	FLOW REGIME: QUANTITY AND VARIABILITY	WATER QUALITY	INSTREAM HABITAT	RIPARIAN	BIOTA
A	Negligible modification from natural.	Negligible modification from natural. Negligible risk to sensitive species. Within Aquatic Ecosystems TWQR (DWAF 1996a) for all constituents.	Negligible modification from natural conditions. Depends on the instream flow and quality objectives which are set.	Negligible modification from natural conditions. There is control of land uses in the riparian zone that ensures negligible modification of vegetation within set distance from banks.	Negligible modification from Reference Conditions, based on the use of a score or index such as SASS (Chutter 1998).
B	Slight risk to especially intolerant biota.	Slight risk to intolerant biota (use Aquatic Ecosystems TWQR and CEV to set objectives) (DWAF 1996a).	Slight modification from natural conditions. Depends on the instream flow and quality objectives which are set.	Slight modification from natural conditions.	Slightly modified from Reference Conditions. Especially intolerant biota may be reduced in numbers or in extent of distribution.
C	Moderate risk to intolerant biota.	Moderate risk to intolerant biota (use Aquatic Ecosystems TWQR and CEV to set objectives) (DWAF 1996a).	Moderate modification from natural conditions. Depends on the instream flow and quality objectives which are set.	Moderate modification from natural conditions.	Moderately modified from Reference Conditions. Especially intolerant biota may be absent from some locations.
D	High risk of loss of intolerant biota.	High risk to intolerant biota (use Aquatic Ecosystems TWQR, CEV and AEV to set objectives) (DWAF 1996a).	High degree of modification from natural conditions. Depends on the instream flow and quality objectives which are set.	High degree of modification from natural conditions.	Highly modified from Reference Conditions. Intolerant biota unlikely to be present.

The EMC is set as part of step 5 in setting the ecological Reserve (Section 4.4). There are different methods for setting the EMC for the various levels of the Reserve. These are outlined in this section, and in detail in DWAF (1999b). The rest of this chapter focuses on the method used for setting the EMC as part of a Comprehensive Reserve Determination (Section 4.6), as would apply when using the BBM.

11.1.1 Setting the Ecological Management Class in Desktop Estimates

The EMC is derived directly from the ecological importance and sensitivity rating (Chapter 10). This reflects the twin philosophies that important and sensitive resources should be assigned a high level of protection, and that in the absence of detailed knowledge of the river, a highly precautionary approach should be taken.

11.1.2 Setting the Ecological Management Class in Rapid Determinations

The EMC is derived directly from the ecological importance and sensitivity rating, but moderated by a shortened, intermediate assessment of habitat integrity. If the river is presently degraded but there is potential for improvement, the selected EMC remains equivalent to that indicated by the ecological importance and sensitivity rating. If the river is presently degraded due to permanent structural modifications, the selected EMC is adjusted to a class achievable within these constraints.

11.1.3 Setting the Ecological Management Class in Intermediate Determinations

In the past, the ‘default rule’ applied, whereby after an intermediate status assessment, the EMC was set in relation to the PES (i.e. the present status). For rivers that were slightly to largely modified, the EMC was set at a level which represented a goal of no further degradation (Table 11.2). For rivers that were critically modified, it was set at a level that represented a move toward improvement. In later applications, the Rapid Determination has become more sophisticated and will probably replace the ‘default rule’.

Table 11.2 Setting Ecological Management Classes in relation to Present Ecological State.

PRESENT ECOLOGICAL STATE ASSESSMENT CATEGORY	ASSIGNED ECOLOGICAL MANAGEMENT CLASS
A	A
B	B
C	C
D	C
E or F	D

11.1.4 Setting the Ecological Management Class in Comprehensive Determinations

A formal process of consultation with and participation by the stakeholders leads to a decision by DWAF on which EMC will be set for the river (see Section 11.2). The guidelines for consultation are included in DWAF (1999c), but have not been tested yet.

11.2 SETTING THE ECOLOGICAL MANAGEMENT CLASS

For a Comprehensive Reserve Determination, deciding on an EMC for a section of river includes input from the BBM specialists involved in recommending flows and water quality for the ecological Reserve. Consideration is also given to stakeholder representatives (Chapters 9 & 10), but the final responsibility for setting the EMC rests with the Minister. This process has yet to be completed at the time of writing, but is underway for sections of the Olifants River (Gauteng, Mpumalanga and Northern Province). The methods developed for the Olifants project will be described here, but may be modified in the light of their final implementation.

11.2.1 The specialist process

The specialists (ecologists, water quality expert, hydrologist, hydraulics engineer, sociologist) first consider the Reference Condition, PES (Section 4.4) and importance (Chapter 10) of the river. This is followed by a specialist workshop at which the sequence of steps in Table 11.3 is followed.

- If the river has degraded from its Reference Condition, the specialists analyse the causes of degradation (e.g. increased salinity), the origin or reasons for the changes (e.g. mining), and how rapidly the changes are occurring (the trajectory).
- The specialists then decide to the best of their knowledge what would have to be done to address the causes of degradation; how effective such remedial actions might be; and how difficult they might be to achieve. For instance, if a major supply dam would have to be eradicated to improve river condition, the remedial action would be classed as very difficult.
- Taking into account the above, and the ecological importance of the river, the specialists then recommend whether the river should be maintained at its present state, or improved and, if the latter, to what degree. If it would be very difficult to improve the condition of the river, a short-term target to maintain it in its present state may be recommended, together with a long-term (10-50 year) target for improvement. Extensive management of the system may be required simply to maintain its present state, especially in cases where the trajectory of change is steep.
- Finally, the specialists consider the ecological consequences for the river if no changes are made to the present management regimes for it and its catchment. This helps stakeholders to understand the long-term ecological results of different management scenarios.

It is important to distinguish between causes of degradation which are related to flow (and can potentially be repaired by instituting a suitable EFR), and those which are not flow related and would require other management actions. For example, cessation of dry season flows in the Letaba River in the Kruger National Park could be reversed by implementing the recommended EFR. However, most of the water quality problems in the neighbouring Olifants River would be dealt with best by addressing point sources of pollution, rather than by recommending dilution flows. Similarly, problems of river condition not related to flow can be found in overgrazed and eroded catchments and riparian zones. In such cases, flow regimes should be recommended using the BBM, in the expectation that concomitant measures will also be taken to cure the non-flow related problems.

Table 11.3 A sequence of questions to be addressed at the specialist Ecological Management Class Workshop to arrive at a recommended EMC and to provide information for stakeholders.

QUESTION	ACTION
What is the river like now compared to the natural state?	Compare Reference Condition and PES (Class A-F).
How ecologically and socially important is the river?	Ascertain importance and sensitivity ratings and state confidence in these evaluations (Low/Moderate/High).
Is the condition of the river changing, and if so how fast and severely?	Ascertain the trajectory of change for each major ecosystem component, with reasons. Trajectory can be: none, shallow, moderate, steep.
What is/are the main cause(s) for the change, and its/their origin(s)?	Identify critical cause(s) for the trajectory of change and relevant origin(s).
Can these causes be negated?	Describe what would be required to redress the causes.
What will happen to river condition if the main problem is solved?	Ascertain if addressing the main causes of change will slow down, halt or reverse river change. The EMC could remain at its present level, or shift, for example, by one class. Response could be short term or long term.
Can the main problem realistically be solved? If not, why not?	Assess the difficulty in solving the problem: Easy; Reasonably easy; Difficult, Very difficult. Describe all possible solutions, and reasons for the difficulty ratings.
What could be realistic ecological aims for the river?	Considering the importance of the river and the difficulty in rehabilitating it, advise whether or not the PES should be improved, and if so, to what degree (Class A-D). Note that maintaining the PES could still require proactive management, depending on the trajectory of change.
How will the river change if nothing is done?	Describe the future condition of the river (Class A-F) in the short and long term if river and catchment use, and river management, continue as at present.

11.2.2 The stakeholder process

Stakeholders are inevitably very diverse in their interests, resources, abilities to grasp the complexities of the new Water Law, and opinions about the state of and objectives for local resources. In the Olifants Catchment (Mpumalanga), for example, stakeholders range from major mining companies, commercial farmers, and municipalities, to conservation bodies and rural communities using the river for sustenance.

The aim of the stakeholder process, which is a vital part of all water-resource developments, is to inform all these groups of the present condition of the river, to canvas their opinions on the acceptability of its present condition, and finally to try to achieve consensus from them on the future condition of the river.

When setting the ecological Reserve, the views and desires of the stakeholders are confined to those that relate to the protection and sustainable management of the resource as a healthy ecosystem. Many stakeholders therefore have a dual role in setting the overall management objectives for the river. On the one hand, they may be offstream users of the resources of the river. On the other hand, they may also be individuals or groups interested in its viability as a sustainable healthy ecosystem catering for all users in the long term. In the EMC process, the stakeholders are asked to look past their short-term desires to exploit the river, and to concentrate on their latter role - that of protectors of the resource. There are other very adequate processes that allow users to voice their offstream requirements from the river, and these should not be allowed to confuse the process of setting the ecological Reserve.

The uses which are legitimately taken into account in setting the ecological Reserve are referred to as those direct uses of the river which depend on the maintenance of a healthy riverine ecosystem. Such uses include washing; swimming; subsistence or recreational fishing; harvesting riparian plants for thatching, medicines and other sustenance uses; cultural or religious practices such as baptisms, boating or canoeing; and wildlife viewing and other non-exploitative ecotourism activities. Uses that are not included are abstraction of water for irrigation, or municipal or industrial use; disposal of bulk effluents; or mining of river sand.

The stakeholder process should start before the specialist process, and should consist of a series of meetings aimed at helping the stakeholders to understand the entire Reserve process. The major input from the stakeholders in the Reserve process is for them to state their opinions with regard to the desired ecological state for the river. The specialists consider these opinions when recommending an EMC. Stakeholder Meetings should adhere to the following sequence.

- An introductory meeting, at which the ecological Reserve process is explained, questions answered, and the various stakeholder groups invited to nominate representatives to participate in the remainder of the process.
- A PES Meeting, at which the specialists present their analyses of the condition of the river, in terms of Classes A-F, with careful explanation. This and subsequent meetings are facilitated by an experienced public participation expert, who is responsible for ensuring adequate stakeholder representation and for guiding the specialists to present their information in a non-scientific, but informative way.
- An EMC Meeting, following the specialist EMC Workshop, at which the specialists present, with explanations, their recommended EMC, and the stakeholders respond. The aim of this meeting is to reach consensus on the ecological objectives for the river.

Between these meetings, the social consultant should hold a series of smaller meetings and interviews to ensure that stakeholders have an adequate understanding of the issues, that representatives of interest groups are informing their constituency, and that the full diversity of opinions has been accessed.

11.2.3 Reaching consensus

There is at present no agreed process for ensuring that consensus is reached as to the appropriate EMC for a water resource. Because of the diverse nature of the stakeholders, there is a strong possibility that different interest groups will wish for different EMCs. If no consensus can be reached, the Minister will make the final decision.

There are, however, pre-set conditions that may help to avoid major disagreements. For instance, possible recommendations for the future EMC are limited by the fact that the new Water Law requires that the EMC be set the same as or higher than the PES. It is also required that the EMC be set within realistic boundaries. This may well mean that the choice of EMC is between the present class and one class higher. If the importance rating of the river is high, the choice would normally be to aim for one class higher, whereas if the importance rating is low, strong justification would be required to improve the river by a class. If the PES is an E or F class, then the default requirement is to set the EMC at D, as a higher class would normally be unrealistic. With these limitations in place, it is likely that consensus can be reached in most cases, and irreconcilable conflict among stakeholders, or between stakeholders and specialists, will be the exception. Where the latter does occur, then arbitration through the Minister is the last resort.

11.3 POTENTIAL PITFALLS

Most of the potential pitfalls of the EMC process have already been mentioned in the previous sections. The following is a summary of the most likely areas where additional difficulties could be experienced.

- Where there is significant specialist capability among the stakeholders, disputes may emerge as to the PES or the potential EMC. This may happen, for instance, when a powerful development lobby tries to set the EMC as low as possible in order to allow for short-term exploitation of the resource.
- The river under consideration may be of exceptional importance, but impacted by intractable conditions in the upstream catchment or channel. A possible example is the Olifants River which runs into the Kruger National Park. The Park’s mission is the maintenance of natural biodiversity, but the mining/industrial complex of Phalaborwa immediately upstream presents water quality and quantity problems that can only be solved by a major restructuring of the industrial area. The stretch of river in the Park requires a high EMC, but realistically, this may be extremely difficult to achieve.
- There will be other kinds of cases where upstream conditions and river importance suggest a low EMC, but downstream sections of the river have a high importance and would rate a high EMC. The downstream high EMC cannot be achieved, however, without major improvements to the upstream sections. In both this and the previous example, where solutions can only be developed in the long term, there should be an interim EMC, with a long-term management plan to achieve the higher EMC.
- Cases may occur where the Reference Condition of the resource is uncertain, because of insufficient information or extensive change. If the Reference Condition is unknown, it is unclear what the Class A river would have been like, what class the present condition thus is, and how to set a future management class. An example is the Mhlatuze River (KwaZulu-Natal) downstream of Goedertrouw Dam, where pre-impoundment aerial photographs indicate a sand bed river. Present conditions are a riffle-pool anastomosing river with diverse habitats, as a result of scouring dam releases. In such situations, either

the present condition may be treated as the Reference Condition, or another comparable river should be sought that could provide an acceptable Reference Condition.

- In some cases, the trajectory of undesirable change may be very steep and extremely difficult to reverse. Such a river could be in an E or F PES because of, for instance, severe overgrazing and extensive catchment erosion. In such cases it may require a long-term catchment management plan to begin to repair the effects of vegetation and soil loss, before the condition of the river will even stabilise. An EFR could be set for such a river, but realistically, it may not be possible to improve its condition even in the medium term.

11.4 FURTHER DEVELOPMENTS

The whole process for setting EMCs with stakeholder participation is in an embryonic form and will improve once the various methods have been tested in a number of different situations. There is no objective method for deciding on the ecological target for a water resource, since the aspirations for the resource are a reflection of the values of the participants in the process. However, there is no reason why the process should not consist of transparent, consistent methods aimed at capturing and reconciling the values of the participants. Development of the process should aim towards this goal.

11.5 CONCLUSIONS

An EMC process with full stakeholder participation is costly and time consuming, but vital in ensuring the understanding and cooperation of all affected parties. Most of the BBM procedures are well developed and defensible, because they are largely based on the objective expertise of acknowledged specialists. However, the setting of EMCs incorporates inputs on the wishes and aspirations of diverse groups of people, and hence will inevitably be vulnerable to criticism. If the process is undertaken honestly and transparently, with all stakeholders able to participate and provided with a constructive and structured opportunity to state their aspirations, then the results can be said to be a fair reflection of the range of opinions of the community, whilst not necessarily their best long-term interests. If the process is flawed, and attempts are made to impose solutions against the will of the participants, then the EMC becomes the most vulnerable component of the Reserve procedure. These are aspects which the Minister may have to consider when approving an EMC that is in the best overall interests of the country.

12. HYDROLOGY

Denis Hughes

12.1 THE HYDROLOGICAL REGIME IN RIVER STRUCTURE AND FUNCTIONING

The hydrological regime is of major importance in the functioning of a river although the nature of its influence will differ for different components of the abiotic and biotic environment. The regime includes and describes all aspects of the hydrological character of a river, and can be viewed over several time scales. At the scale of years, the regime reflects the annual variability of flows and the extent to which this variability is cyclical (e.g. does the river experience extended periods of below average flow, followed by periods of above average flow?). At the scale of months, the regime reflects the seasonal distribution of flows and the extent to which this distribution is consistent during dry and wet periods. For example, dry years may be characterised by some wet season flows combined with a failure of dry season baseflows. Alternatively, dry years may be characterised by failure of the wet season flows while the dry season flows are maintained. At this scale it is also important to recognise whether a river is permanently flowing (perennial), seasonally flowing (intermittent) or occasionally flowing (ephemeral). At the scale of days (or shorter periods), the regime reflects, for instance, the rate of increase of flow at the start of a flood event and the rate of decrease, or recession, at the end. It also reflects the number of events that are expected to occur at any time during the year and their size (peak, volume and duration). The timing, frequency and duration of extreme droughts and floods are also important hydrological characteristics of the flow regime.

These various hydrological characteristics have a direct effect on ecological and geomorphological processes that occur within the river channel and riparian environments. Some processes will be more closely associated with certain aspects of the regime than with others. For example, the shape and size of the channel is largely determined by the flood regime, while spawning of many fish species is related to the occurrence of freshes (small pulses of higher flow in the dry season). While the natural hydrological regime of a river is largely determined by climate and catchment characteristics, channel and riverine ecosystem processes may also impact directly on the flow regime itself, creating feedback mechanisms. Examples of the latter include channel transmission losses, that is, losses from the channel into the bed or bank. These are affected by the characteristics of the wetted perimeter and riparian vegetation, which in turn are affected by modifications to the regime.

Very few rivers in South Africa and other parts of the developed world still have natural flow regimes; most are now impacted by water-resource developments and changes in land use. It is therefore necessary to distinguish between natural and modified regimes, and to ascertain whether the modifications are continually changing and the time scale over which they are taking place. The latter is important, as many ecosystem riverine processes may be buffered against streamflow changes, and so secondary effects might lag behind changes in the flow regime. For example, because of the natural variability inherent in flow regimes, a short-term decrease in flows might well be within the norm for the river and cause no undue ecosystem response. However, if such a flow reduction was to persist under a modified regime, substantial and permanent ecosystem changes could take place.

In this chapter, recognition is made of both natural and modified flow regimes in the following way:

- **natural (virgin)** – the flow regime with no anthropogenic influences;
- **historical** – the flow regime experienced in the past, which could include highly variable anthropogenic modifications rather than fixed, present-day ones;
- **present day** – the flow regime based on fixed, present-day levels of anthropogenic influences (e.g. land-use modifications; abstractions; return flows; reservoirs).

12.2 HYDROLOGY IN THE BUILDING BLOCK METHODOLOGY

The hydrological functioning of the river is not important *per se*. Rather, it is the impact of different hydrological regimes on the ecological functioning of the river that is of primary concern. The hydrological information can therefore be viewed as ‘service’ data.

Within the BBM, the objective of these ‘service’ data is to provide as complete a picture as possible of the hydrological regime of the river, including both its natural and modified characteristics. This will allow the other components of the river ecosystem to be placed in the correct context, and the development of a better understanding of the site-specific relationships between hydrology and other river processes. However, these relationships are complex and difficult to understand, and they may not be precisely established if time for preparation for an application of the BBM is limited.

Many of the other specialists attending the BBM Workshop may be unfamiliar with hydrological data and the analytical methods used by hydrologists. It is therefore important that the information is presented in a clear way that is easily understood. Visual information, such as hydrographs and FDCs, is frequently easier to absorb than numerical data.

Hydrological data are related to other biophysical knowledge through derived hydraulic relationships, usually through the links between water depths and velocities, and discharges (Chapter 13). These relationships are derived using short-term discharge data. Such detailed hydrological data sets are rarely readily available, and are difficult and time consuming to simulate. Time series of mean daily discharge may be accessible, but often only monthly volumes are available. These latter data may well have been compiled for the yield analysis of the water-resource scheme being designed, and can be useful for describing periods of little flow variation (dry seasons). However, they are of little value for wet or intermediate seasons, because they do not describe the detail of floods and low flows. For these seasons, daily data are required.

It has been common practice to base flow assessments using the BBM on the natural flow regime of the river, that is, with all impacts of upstream developments removed, on the assumption that this is the condition against which the future modified regime should be compared. This is a logical approach, given that the designated EMC for the river can range from totally natural (pristine) to critically modified (Chapter 11). It would not be logical to consider only the present-day regime if the EMC were to be set at a closer to natural level, as there would be no information on the natural upper limit of flows to guide discussions on how to upgrade the condition of the river. Ideally, information on both regimes (natural and present day) should be made available, so that the new recommended flow regime can be logically described in terms of both present and past flow conditions. Some specialists have suggested that in cases where an upstream development has been active for a long period of time (for instance, some South African headwater areas have been afforested for over 40 years), only the modified regime should be used. This is presumably based on the premise that it would be difficult to determine what the natural riverine environment would have been, as it lies outside present day human experience. Any evaluations of the functioning of the river in the present and recent past, forming the basis for the EMC, would thus be likely to ignore modifications that occurred many years ago. In these cases, a decision has to be made as to whether the natural or modified flow regime should be used as the Reference Condition.

12.3 MINIMUM AND IDEAL DATA SETS

As stated earlier, the ideal data set for a BBM application is a daily time series of observed flow data measured at, or close, to each BBM site. The data set should be sufficiently long to represent the range of conditions (wet and dry extremes) that naturally occurred. If the observed data represent a flow regime greatly modified from natural, then it may be necessary to simulate parallel data sets of natural and present-day conditions (Section 12.2). Simulation may also be necessary to extend the length of a short, but otherwise ideal, data set.

Given such information, it is a relatively straightforward task to characterise the hydrological regime, assuming that suitable software for time series analysis is available. However, given the low density of flow gauging sites in most countries, it will not normally be possible to select sites to coincide with gauging stations. Even where this is possible, some part of the record might be influenced by upstream impacts, and the data might thus not be representative of natural conditions. Within South Africa, the most complete reference source for natural streamflow characteristics is the Surface Water Resources of South Africa 1990 (WR90 - Midgley *et al*., 1994b). However, these data (simulated for 1920-1988) are based on monthly flow volumes and presented at a relatively coarse geographical scale (using catchments between 30 km^2 and several hundred km^2). The following list (Sections 12.3.1-12.3.4) represents the range of possible scenarios of data availability, as well as possible actions that can be taken to make the best use of the data in preparation for advising on a future flow regime.

12.3.1 Observed data at, or close to, the site

If the data set is long, sufficiently complete and representative of natural conditions, then no further preparation is required. If the data set represents natural conditions, but is not long or sufficiently complete, there are relatively simple techniques available for patching and extension (e.g. Hughes & Smakhtin 1996) as long as longer records are available from a nearby gauged catchment with a similar flow regime. Alternatively, a daily time series simulation model (stochastic or deterministic) could be calibrated against the observed data and then used to simulate a longer data series (Hughes & Sami 1994, and Schulze 1995, provide examples of the use of deterministic rainfall-runoff models). This latter alternative represents a potentially time consuming approach, which may not be appropriate if there are time constraints, and so should be avoided if simpler techniques can be used.

If the data are not natural over a long enough period, both natural and present day estimations may be required. Simple patching and extension approaches can still be used, but with more difficulty. Within South Africa, the monthly WR90 data can be useful to guide and check the naturalisation process. Although time consuming, the deterministic modelling approach becomes more attractive under these circumstances, particularly if the upstream influences are reasonably well defined and highly dynamic over the period of recorded data. The final choice is frequently based on the available time resources.

12.3.2 Observed data on the same river, but distant from the site

This is a fairly common situation and several options are available, again depending upon the length of the data set and the completeness and extent of upstream impacts. Any necessary naturalisation, patching and extension of the observed data can be carried out using the same methods as outlined in Section 12.3.1. It is then necessary to carry out the geographical interpolation to the site of interest. This would normally be done using either linear interpolation, such as multiplication by the ratio of the catchment areas or mean annual runoffs at the two sites, or a non-linear approach. Various non-linear approaches are possible depending upon how much is known, or can be inferred, about the differences between the regimes at the two sites. Effectively, they will all apply differential scaling factors to different discharges or to flows occurring at different times of the year. These may be based upon some understanding of the characteristics of tributary inflows between the two sites. The difficulty with simple, seasonally varying scaling factors is the potential problem of generating spurious discontinuities at month ends.

12.3.3 Observed data for an adjacent river(s)

The approach for this data scenario is very similar to the previous one, except that a great deal of care needs to be exercised to ensure that relatively simple scaling factors (linear or non-linear) can be realistically applied. This is particularly the case if the catchment areas of the two sites are very different. Regional monthly data (e.g. WR90 data for South Africa) can help to confirm or deny this at the monthly scale, and a regional analysis of all flow gauging records can be used to assess the degree of consistency in regime characteristics across catchments of different sizes.

The rainfall-runoff modelling option is also available under the first two scenarios, and the approach would be to calibrate the model against available observed data in the vicinity and then apply parameter transfer techniques to develop a flow time series at the site of interest. The earlier comment about time constraints applies equally here.

12.3.4 No observed data in the vicinity of the site

This is the most difficult scenario, as there is virtually no information available with which to assess the quality of any simulations. The simplest and shortest approach would be to use any available simulated monthly data of volumes, together with some suitable method for disaggregating these volumes into daily information (see Schultz *et al.*, 1995, for an example). None of the available disaggregation approaches has been very widely tested and therefore these cannot be considered robust at the time of writing. However, further research is in progress to improve such methods. The other alternative is the rainfall-runoff modelling approach, although this is time consuming and there are no available observed data with which to calibrate or validate the results.

The final choice of approach will be determined by the availability and quality of the observed flow data, as well as by the amount of supporting data (e.g. catchment characteristics, water abstractions) that are readily available to assist modelling studies. If the latter data are not very detailed, it will be difficult to express a high level of confidence in the results of complex modelling approaches, and a simpler, less time intensive approach may be more appropriate.

12.4 SEQUENCE OF ACTIVITIES

The exact nature of the required activities will depend upon the suitability of the available observed data, as referred to above. However, some general statements can be made. All of the hydrological work can be carried out as desk studies, although it is preferable that the hydrological consultants either be familiar with the region, or spend a short amount of time in the field familiarising themselves with the character of the catchment upstream of each BBM site. It is recommended that all the activities be carried out by a single, experienced hydrological group. This ensures that a complete understanding of the data, their sources and limitations, as well as the analytical techniques used and their limitations, are retained and can be conveyed to the other specialists as needed. Where modelling studies are considered necessary, a separate specialist group or individual could carry these out, as long as the limitations of the results are reported back to the main consultant.

Wherever possible, the objective should be to characterise the natural and present-day flow regimes and highlight their differences, although in some cases a comparison between natural and historical data sets may be more appropriate and simpler to achieve. There are also situations where the natural flow regime would be very difficult to determine and might not be particularly relevant, due to a long history of flow modifications in the river (e.g. the Vaal River).

12.4.1 Acquisition of the observed hydrological data

Most countries have a national repository for streamflow data. For South African rivers, the DWAF Directorate of Hydrology manages such databases, while other countries of southern Africa have equivalent state departments. There are several DWAF publications which list the gauging stations and provide details such as their locations, catchment areas and lengths of record. These can be used to make an initial selection of suitable gauge data, once the approximate location of the BBM sites has been ascertained (Chapter 7). It is also necessary to obtain, from the database manager, a clear assessment of the accuracy level of the gauged data. There may also be information available on the extent of upstream abstractions, either as time series of abstraction volumes, from data contained within other publications or from records of abstraction licenses. Any of these sources can be useful when naturalising flow records of rivers that have been affected by upstream water-resource developments. In South Africa, it is recommended that the WR90 publications and data (available on CD-ROM) be consulted to obtain an initial impression of the natural flow regime of the river at a monthly time scale. The DWAF can also provide examples of typical hydrographs, based on breakpoint stage data. These can be used, in combination with the stage-discharge rating curve for the gauge site, to determine the timing and shape characteristics of flood events. The specific periods requested would normally be selected from the daily flow records, as the complete data set is large and difficult to process. In other countries, the availability of such detailed information will depend upon the gauging method and the way in which the raw data are stored.

If it is likely that a rainfall-runoff modelling approach is required, then the equivalent state agency responsible for meteorological data should be contacted for access to rainfall data. Within South Africa, the relevant organisations are the Weather Bureau or the Computing Centre for Water Research at the University of Natal, Pietermaritzburg, KwaZulu-Natal (CCWR). No further details are provided here about how to proceed with selecting rainfall stations as it is assumed that experienced modellers will be carrying out this exercise, and that they will know the appropriate procedures. Similarly, suitable data on evaporation and catchment characteristics also will have to be collected.

Different countries have developed various policies regarding making data available. While data collected at taxpayers’ expense are frequently available free of charge, this is by no means always the case. There are trends worldwide to privatise some of the state departments that are responsible for the collection of hydrometeorological data, which could impact on policies regarding data distribution.

12.4.2 Generation of suitable daily time series for each site

As already mentioned, this activity can take several different forms depending upon the nature of the observed data, but it is probably the most critical and usually most difficult activity of the whole hydrology study. If a modelling, or relatively complex spatial extrapolation, method is required, then only those groups or individuals that have the appropriate experience should be used. It will be very rare for some form of extrapolation approach not to be required, as few BBM studies will be supported by observed data for every study site. Similarly, in most situations, some form of data naturalisation will be necessary. A regional assessment of available records, and particularly of the characteristics of annual and seasonal non-dimensional duration curves, can be a valuable exercise when deciding which data to use and how to process them to get the best results in terms of representative time series for the sites. Comparing the characteristics of the daily observed data with any available naturalised monthly data can also provide valuable information about the extent to which the observed data require naturalisation. It should always be recognised, however, that if the monthly data are also simulated, they are subject to some degree of inaccuracy, while the observed data may also be subject to ill-defined errors or artificial influences. Although these recommendations may mean accessing more data initially, modern hydrological software allows large data sets to be summarised rapidly and the small amount of additional time taken can save more time later.

It is difficult to offer clear guidelines about selecting a specific approach, and suffice it to say that the results should be the best that can be achieved given the data and time constraints. It is likely that the hydrological consultants will use those techniques that they are most familiar with and have the most confidence in. The main consideration, therefore, is to select consultants who have sufficient experience in this field, and who have access to reasonably well tested techniques which have been developed for this, or related, purposes. Different groups may use different techniques, but should come up with similar answers, given the same input information. The final result should be the generation of time series that are sufficiently long to represent the natural and modified flow regimes at the sites of interest. The length of the time series will depend upon the regime characteristics, and should be longer (probably greater than 30 years) for more variable regimes. The objective is to adequately represent wet and dry periods. In a southern African context, it is fortunate that most parts of the region have experienced both extremes in recent years, during which time streamflow gauges have been operational.

The main steps for this activity are summarised below.

- Identify and quantify any artificial influences on observed hydrological data, including any indications that the data will be non-stationary.
- Carry out a regional analysis to determine the spatial variability of flow regime characteristics within the study area, taking the results of the first step into account. This exercise will assist with determining how far from the BBM site observed data can be expected to be representative.
- Select an appropriate spatial extrapolation approach, where the data suggest that this approach will be satisfactory. Use the selected method to generate time series for each site and adjust, as necessary, to represent both natural and present-day conditions.
- If the previous step is unlikely to be successful, set up, calibrate and validate a rainfall-runoff model. Once validated, generate two sufficiently long time series of streamflows, to represent natural and present-day conditions.

12.4.3 Generation of summary tables and graphs for the workshop starter document

There are a great many different ways of displaying graphs or compiling tables of time series data to illustrate the regime characteristics of a river. All can be useful, and individual methods frequently complement each other. Far too much space would be taken up in the starter documentation for the BBM Workshop (Chapter 20) if they were all to be used. Therefore, the best approach is to include a few that illustrate the essential characteristics of the regime at different sites and time scales, and to make other information available at the workshop.

The hydrology section of the starter document should begin with a brief description of the data sources, their quality and limitations and the techniques that were used to generate the time series of streamflows for the BBM sites. Coupled to this should be a description of the main artificial influences, their known history and the extent to which they affect the flows in the river(s). It is also essential to include a schematic diagram, showing the main river(s) and major tributaries, gauging sites, dam or abstraction sites and BBM sites (Figure 12.1). The present-day and natural, mean and median annual runoff values at key points should also be provided on the diagram.

The following graphs or tables should be included, wherever possible:

- Histograms of annual streamflow volume (natural, and present day or historical), to illustrate the variability of the annual flow regime and to allow ready identification of wet and dry years (Figure 12.2).
- Seasonal distributions of flow volume (natural and present day or historical) for up to three wet, three intermediate and three dry years (Figure 12.3).
- One-day, annual FDCs for natural and present-day or historical conditions. A logarithmic vertical axis should be used so that the range of both high and low flows can be readily identified (Figure 12.4). Flow duration curves for individual calendar months can also be very useful.
- Examples of annual time series of daily flows for wet and dry years (natural and present day or historical). These allow the workshop participants to visualise the shorter-term baseflow response and flood event characteristics of the river, under different climatic conditions (Figure 12.5).

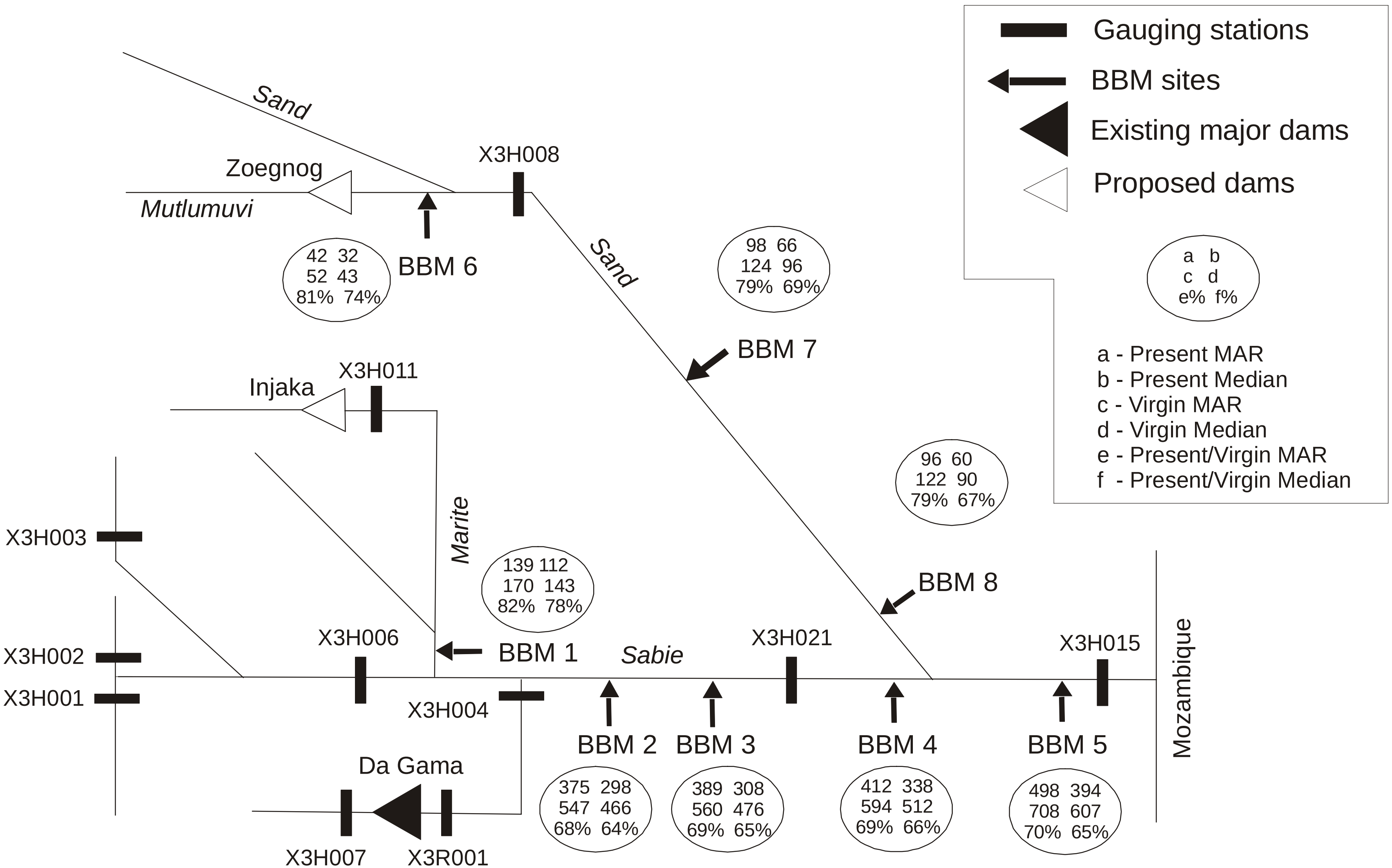


Figure 12.1 **Schematic diagram of the Sabie River System (Mpumalanga), showing flow gauging sites, BBM sites and present or planned major impoundments (from DWAF 1996b).**

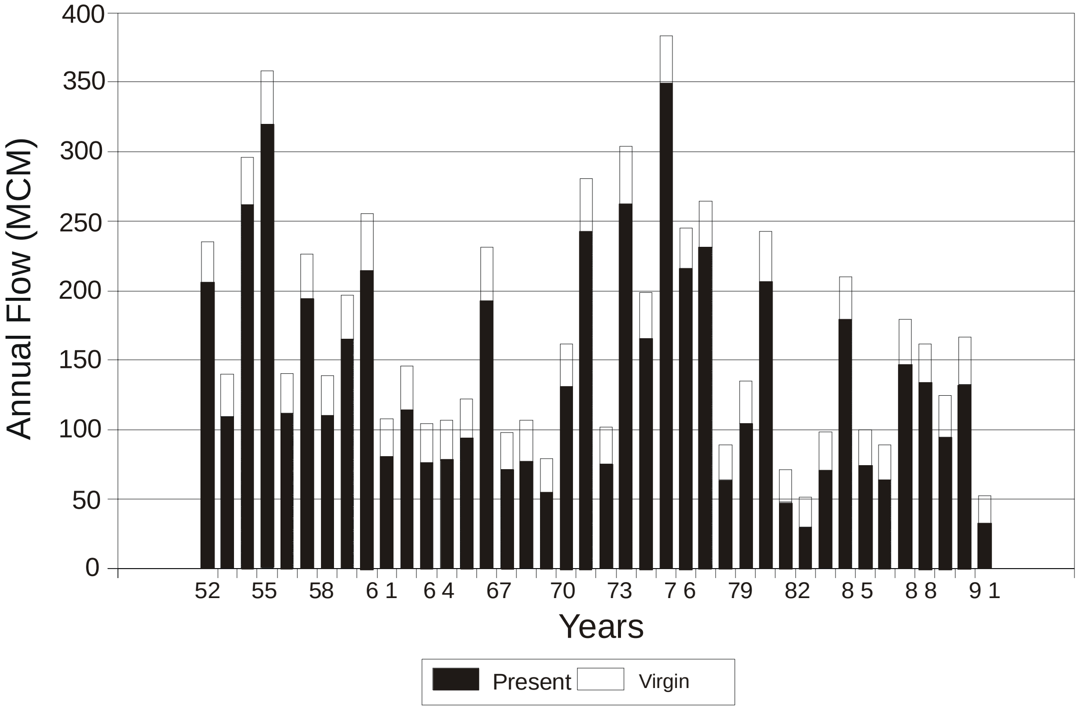


Figure 12.2 Annual present-day and virgin flow volumes for the Marite River, Mpumalanga, BBM site 1 (from DWAF 1996b). MCM - 10^6 x m^3.

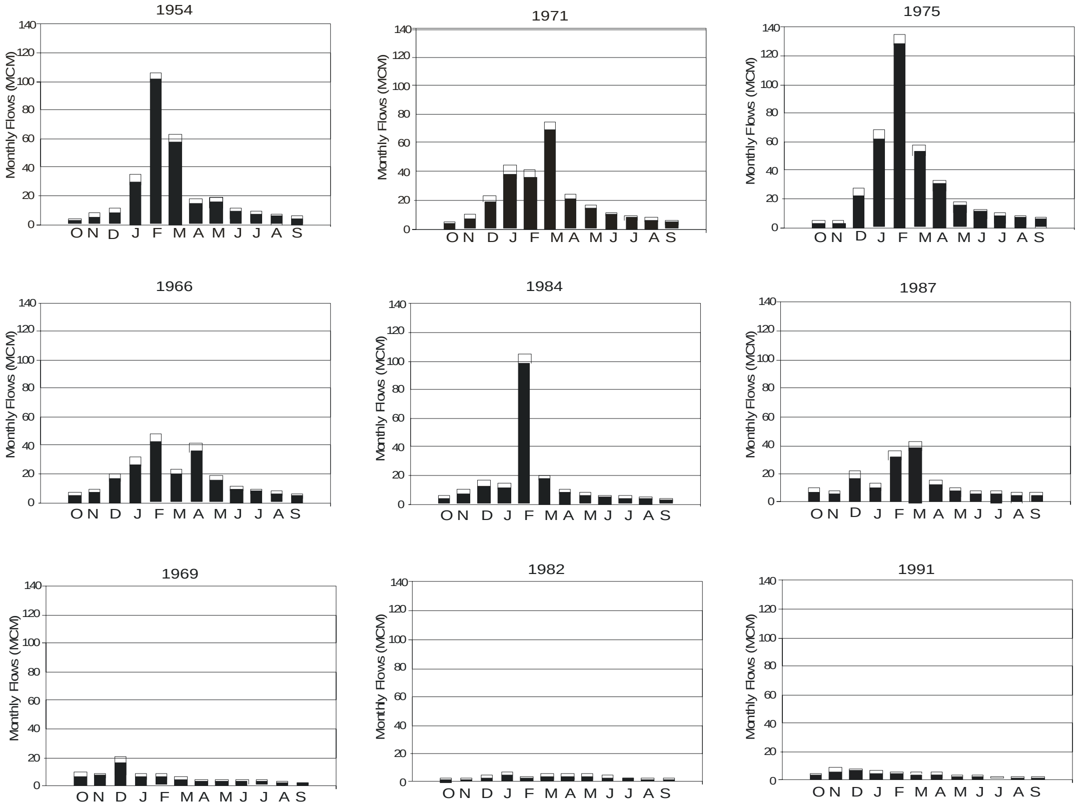


Figure 12.3 Monthly distributions of natural and present-day flow volumes for three wet (1954, 1971, 1975), three intermediate (1966, 1984, 1987) and three dry (1969, 1982, 1991) years, for the Marite River, BBM site 1 (from DWAF 1996b). MCM - m^3 x 10^6.

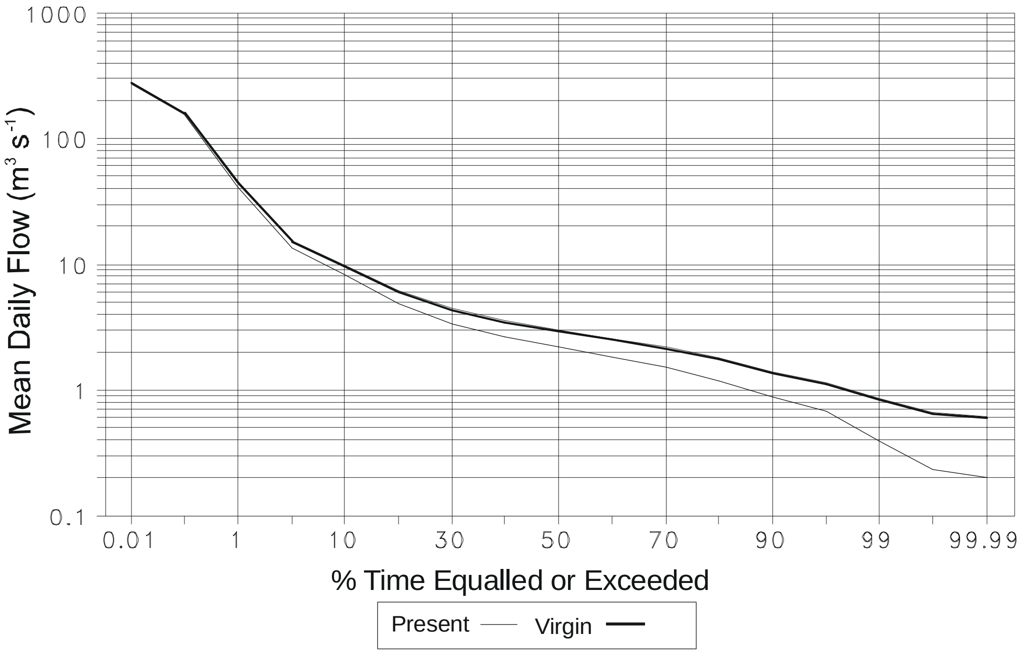


Figure 12.4 One-day annual FDCs for present-day and virgin flow regimes, for the Marite River, BBM site 1 (from DWAF 1996b).

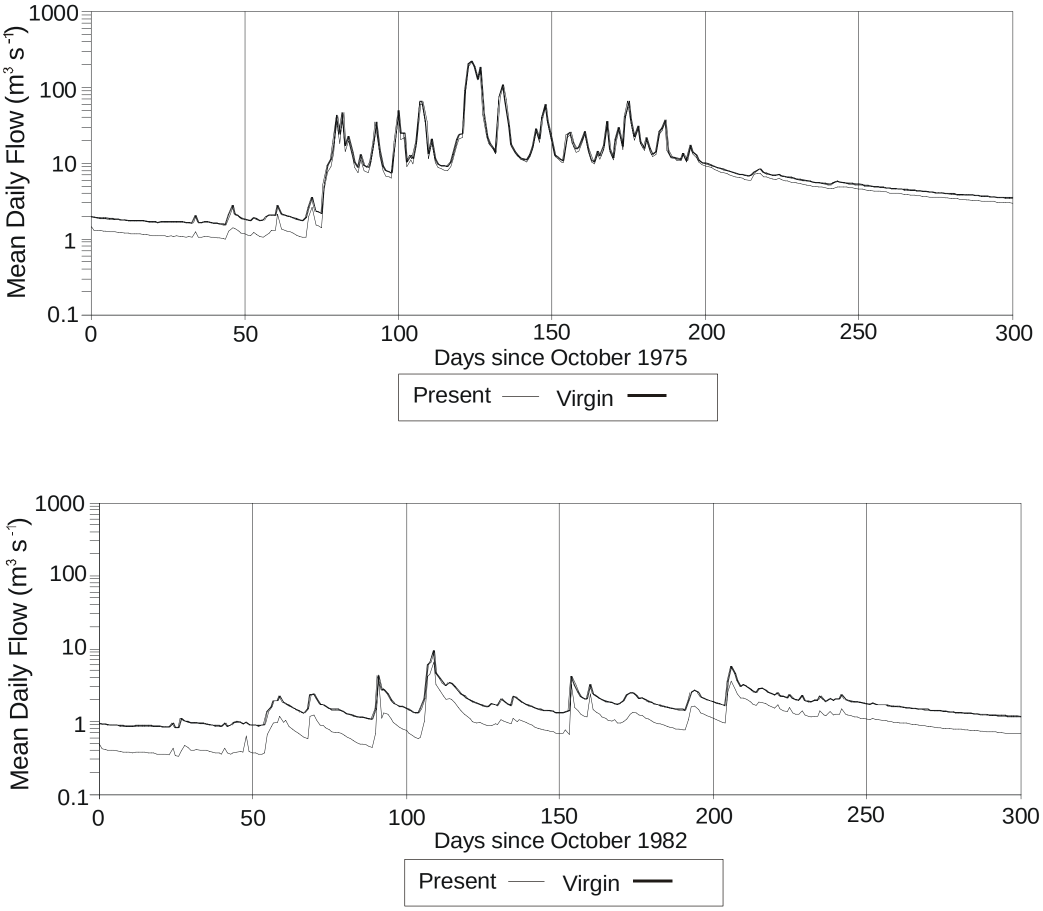


Figure 12.5 Present-day and virgin daily time series for the Marite River, BBM site 1, one wet (1975) and one dry (1982) year (from DWAF 1996b).

- Some information on the peak, duration and shape of flood events. This information can be included in a table that quantifies the range of baseflows, the expected number of high flow events, the range of peak flows and durations of events for each month of the year (Table 12.1). This information can then be used in conjunction with the hydraulic data to obtain a better understanding of the frequency with which different parts of the river channel are inundated. For the same reason, it is also necessary to attempt to estimate some flood peaks with greater return periods (i.e. floods with a return period of 1, 2, 3, 5 and 10 years). In some circumstances, examples of flood hydrographs based on events shorter than one day may be available, and can be included. These contribute to the description of the character (duration, peak discharge, recession rate) of flood events.

Tables for each year of the record, of ranked minimum, mean and maximum daily flows for each month of the year, have been used in some previous workshop documentation. It is, however, unclear to what extent participants prefer this type of tabulated information to graphical displays of similar information such as time series plots, box-and-whisker plots and FDCs.

Table 12.1 Summary of flow data for 40 years (natural conditions) for the Marite River (Mpumalanga) BBM site 1 (from DWAF 1996b). Flows are in $m^3 s^{-1}$ and durations in days.

MONTH	RANGE OF BASEFLOWS	NUMBER OF EVENTS	RANGE OF PEAKS	MAIN DURATION
Oct	0.8-3.0	1	6-18	2-3
Nov	0.9-3.0	1	10-65	2
Dec	1.0-3.5	3	12-130	2-4
Jan	1.5-3.5	3	20-224	2-3
Feb	1.5-5.0	3	48-320	2-3
Mar	1.5-7.0	3	20-160	2
Apr	1.5-6.5	< 2	10-44	2
May	1.0-6.0	< 1	4-12	2
Jun	1.0-5.0	< 1	4-11	2
Jul	0.9-4.5	< 1	5-9	2
Aug	0.8-4.0	0	-	-
Sep	0.8-3.0	1	5-30	2

12.4.4 Preparation for the workshop

Once the daily time series have been generated, the main preparation for the BBM Workshop is to ensure that the necessary interactive time series data analysis and display software is available and can be used efficiently during the workshop. If this cannot be done, then a great deal more effort is required to generate paper copies of summary information prior to the workshop. The following graphical or tabular information may be required (reference can be made to Smakhtin & Watkins 1997, for further details of some of the analysis procedures).

- Annual plots of streamflow volume.
- Seasonal plots of mean monthly streamflow volume using selected, not necessarily concurrent, years, so that seasonal patterns of the response of streamflow to different climatic conditions can be visualised.
- Plots of daily time series for one or more sites, overlain for comparison for any length of period from one or two months up to more than ten years. Ideally, these plots should be scalable so that the detail of low or high flows can be concentrated on. It has also been found useful to produce wall posters of such plots for quick reference. These allow the specialists to view some representative time series, and discuss as a group trends or specific regime characteristics. Ideally, the displays should consist of plots of several years of data for each identified season, with dry, wet and intermediate years plotted separately.
- Several plots of daily time series for the same site, but the data for the same months or season from different years overlain. Comparisons can then be made between dry and wetter years, as well as between conditions that typically occur during dry, intermediate or wet years, and the variation of those conditions. As with the other time series plots, these should be scalable. This information is useful for ascertaining the frequency with which certain conditions or events prevail. It could, for example, include the date range in which the first minor flood event of the wet season occurs and how often this fails during drought periods. It could also illustrate the month(s) in which the main flow events of the year occur, or the likelihood of not having a rise in baseflow during the wet season.
- Flow duration curve plots using annual data, groups of months or individual months. Duration curves can be compiled using individual daily values or some integration interval (7-day and 10-day intervals are common) to allow short-term fluctuations to be smoothed. Some hydrologists have commented that compiling an FDC based on non-continuous data (e.g. using data only from the months of January) is not strictly a correct procedure. However, if it is thought of as a plot of the proportion of time that certain flows, which do occur during the selected month(s), are equalled or exceeded, then this author considers it a legitimate analysis tool and a very useful one for BBM purposes. Combining such data with the hydraulic data provides information on the frequency with which different physical and biological features of the river channel are inundated during different months of the year.
- Flow duration curve analyses ignore sequences of events and do not provide information on the persistence of flows of certain magnitudes, but only on how frequently they occur. Run, or spell, analyses are therefore very useful adjuncts to FDC analyses. They determine the lengths of time, and how often, discharges are likely to remain below, or above, defined flow thresholds. For example, an FDC analysis can show which discharge was exceeded for 85% of the time; the implication then is that lower flows occurred for 15%, or approximately 547 days, over a ten-year period. A run analysis will provide information on whether these low flow periods occurred often with relatively short duration, or infrequently with longer duration.
- Low flow frequency analysis identifies the lowest flows (over a defined duration) in each year of record, and quantifies the expected low flows, given defined return periods. To work successfully, particularly for long return periods, relatively long (> 30 years) time series are required and it is useful to have some

knowledge of the best theoretical distribution of extreme values for the region. These analyses can be carried out using data for the whole year, seasons or single months.

- Flood frequency analyses can also be carried out in a similar way to those for low flows. However, it should be remembered that many countries mainly store flow data as mean daily flows and do not record instantaneous peaks. This may not be a critical issue for large rivers that have floods of long duration, but could be important for smaller rivers or ones with ‘flashy’ flood regimes. Flashy rivers may have flood events with durations of one day or less, and so mean monthly data are insufficient to evaluate peak discharges. In South Africa, a database of instantaneous flood peaks is also available for some of the gauging stations. However, many of the gauges are not equipped to accurately monitor very high flows, and the data for years prior to the 1960s were mostly based on manual, daily stage plate readings rather than a continuous recording. These data cannot be considered reliable for flood peak analysis. Data on instantaneous peaks are primarily required for geomorphological purposes (Chapter 14), but it is worth remembering when advising on future flows that large floods, possibly required for channel maintenance purposes, are generally not easy to deliver from a water-resource scheme that has been planned primarily for the purpose of water supply.

The **IFR Model** (Hughes *et al.*, 1997) and the **DAMIFR Model** (Hughes & Ziervogel 1998) have been developed to allow the output from the BBM Workshop, which is a modified flow regime, to be assessed. This is done by generating a modified time series based on the recommended flows, and on sets of operating rules for dam releases. If one or more of the models are to be calibrated and run during the workshop, then it is necessary to prepare the data and model parameter files. The IFR Model generates a time series of flow releases which are independent of consideration of the planned water-resource development and its operation, that is, only the recommended flow regime from the workshop is considered. A number of inputs are required for the modelling exercise.

- A reference daily time series of flows that can represent the climatically controlled streamflow variations at the BBM sites. This should be a time series that can also be generated for future periods and should reflect the same Reference Conditions that were used to establish the flow requirements in the workshop. It does not have to represent actual flows at the sites. It may be an observed record or simulated data.
- Data files for the initial operating rules, which determine when flow conditions of maintenance and above, between maintenance and drought, or drought, occur within the modified time series. Modification of these rules, to obtain patterns of flow variation that are acceptable to the specialists, is the objective of the model calibration procedure.

The DAMIFR Model takes into account likely conflicts between the requirements to satisfy the demands of the water-resource scheme and the EFR (as defined by the IFR Model output). There are a number of additional information requirements.

- A daily time series of inflows to the proposed dam, as well as time series of tributary inflows along the length of the river between the dam site and the BBM sites.
- Information about the planned capacity of the reservoir, and the likely abstraction demand including the seasonal distribution. Data on the surface area-to-volume relationship for the reservoir are also necessary for the estimation of evaporative losses.
- A daily time series, or a seasonal distribution, of potential evaporation values.

- Data files for the initial reservoir operating rules, which will then be edited to present various scenarios at the workshop.

It is unlikely that the DAMIFR Model will be utilised to its full potential during the workshop, as that is really part of the later scenario planning process. However, it could be useful to carry out some initial scenario runs, in order to determine the approximate feasibility of the EFR established during the workshop being met after the development is implemented.

12.5 STARTER DOCUMENTATION FOR THE WORKSHOP

With respect to hydrological data, this topic has largely been covered in Section 12.4.3 above. These data have to be viewed in the context of the information available about other aspects of river functioning, and this integration usually takes place during the group discussions at the workshop. It is the author's opinion, therefore, that it is only necessary to provide a limited amount of hydrological data in the starter document, as long as a full range of data analysis and display facilities are available at the workshop. General impressions of the characteristics of the modified flow regime, gleaned from the starter document, can then be supplemented during the workshop by more detailed information, and specific queries can be answered efficiently and quickly.

12.6 ROLES AND RESPONSIBILITIES AT THE WORKSHOP

The primary role of the hydrologist at the workshop is to service the requests of the other specialists, by providing and interpreting hydrological information. Thus, suitable time series analysis and display software should be available, and the hydrologist should be familiar with its use. The starter document should provide some background information about the reliability, limitations and representativeness of the data. However, it is essential to emphasise these points again at the workshop, so that the other participants do not develop false expectations of the accuracy of the hydrological information. Where accurate and reliable natural time series data are not available, it is necessary for the hydrologist to be able to offer advice with respect to likely natural values, and to suggest some measure of the confidence that can be expressed in such estimates.

It is not the hydrologist's role to suggest what the characteristics of the modified regime should be, but only to assist the other specialists in placing their estimates of the environmental requirements into some hydrological context. For example, at some previous workshops the participants decided to identify low flow requirements for several key months and then estimate requirements for the other months through extrapolation. The hydrologist was asked to identify key low flow months from an hydrological perspective, and to carry out the extrapolation to ensure that a muted version of the natural seasonal distribution was retained. If this is to be done, it is necessary to decide whether to use a seasonal distribution using total flows or one using only baseflows.

The type of information that the hydrologist can be asked for will vary a great deal and is not easily summarised. Almost any request for information about the regime characteristics may be expected. Where multiple BBM sites are involved at the same workshop, it may be necessary to carry out a matching exercise toward the end of the workshop. This is done to ensure that the flows recommended at the different sites are reasonably consistent and realistic given the natural or artificial processes that will influence inflows or losses between the sites. The matching exercise may not be a simple task, and it may be difficult to estimate how flows will change as they are translated through a river system experiencing a modified flow regime. Nevertheless, the hydrological consultant should be prepared to make initial estimations, which may be refined at a later stage (i.e. prior to the Scenario Meetings - see Chapter 22) using more information and appropriate routing techniques.

If the IFR Model (Hughes *et al.*, 1997) is to be run during the workshop, then the hydrologist will be required to calibrate the parameters (operating rules) of the model to establish a time series of releases that approximates the EFR described by the specialists. This will be an iterative procedure, where the time spent on the task is reduced if the hydrologist understands the model and particularly the sensitivity of the results to parameter changes. The other specialists also need to have a reasonably clear and consistent perception of what the modified time series of flows should look like. The output from the model allows establishment of a reasonably precise value for the percentage of the MAR that has been requested as the EFR (i.e. the ecological Reserve). This is because the proportions of time that the maintenance or drought, low and flood flow requirements are requested can be defined for a representative period. Table 12.2 provides an example of the summary output provided by the model.

It is not clear at this level of development of the BBM whether it is appropriate to run the DAMIFR Model at the BBM Workshop. It may be more appropriate to do this at the Scenario Meetings that take place later. If attempts are made to use it at the workshop, it is likely to threaten the principle that EFRs should be set independently of any other water use requirements.

12.7 ROLES AND RESPONSIBILITIES AFTER THE WORKSHOP

12.7.1 Generating a representative time series of Environmental Flow Requirement monthly volumes

If the IFR Model has been used during the workshop, the hydrologist will be required to aggregate the daily time series of EFRs into monthly flow volumes, so that these can be used by the group carrying out the water resource planning assessment and reservoir yield analyses. If the model has not been used during the workshop, it may be necessary to set it up, calibrate it in cooperation with a representative sub-group of the workshop participants, and then produce the monthly summary data and pass these on to the water resource systems engineers.

Table 12.2 Example of the output from the IFR Model: mean annual values for a 21-year period based on a site on the Thukela River, KwaZulu-Natal. All volume data (V) are expressed as m^3 x 10^6. % Time - percent of time equalled or exceeded in that calendar month's 1-day FDC.

MONTH	LOW FLOW RELEASES							FLOOD RELEASES	
	Total V	Greater or equal to Maintenance		Between Maintenance and Drought		At Drought		V	No. of days
		V	% Time	V	% Time	V	% Time		
Oct	8.3	7.1	77	0.8	12	0.4	10	1.1	7
Nov	13.0	11.8	82	0.7	7	0.5	9	2.8	12
Dec	20.1	19.2	91	0.4	2	0.5	5	13.7	14
Jan	23.5	22.5	91	0.3	2	0.7	6	14.9	14
Feb	24.4	22.8	88	1.2	7	0.4	4	58.9	31
Mar	23.8	22.6	91	1.0	6	0.2	2	13.1	14
Apr	18.9	17.8	88	0.4	3	0.7	8	4.6	13
May	13.8	13.3	92	0.4	4	0.1	2	0	0
Jun	9.8	9.2	90	0.4	4	0.2	4	0	0
Jul	6.9	6.5	90	0.4	8	0.0	1	0	0
Aug	5.5	5.1	87	0.2	3	0.2	8	0	0
Sep	5.5	5.2	90	0.3	8	0.0	0	0	0
Annual	173.4	163.1	88	6.5	6	3.9	6	109.1	

12.7.2 Preparation for and attendance at the Scenario Meetings

This is the most appropriate time for the DAMIFR Model to be applied, if required. The main activities will be to compile the necessary data as outlined in Section 12.4.4, and to run the model for a variety of scenarios. The resource planning team will supply information such as seasonal distributions of design abstractions and initial required reliability, which will be used to specify some of the model's operating rules. Other operating rules will be established by the hydrologist, in order to represent various scenarios. The model is able to simulate, under situations of limited water availability, different levels of priority balance between satisfying the EFR and abstraction demands. It is not the hydrologist's responsibility to determine these priorities, but merely to illustrate the consequences of different options.

12.8 EXAMPLE OF TERMS OF REFERENCE

The following list represents a comprehensive Terms of Reference; some of the tasks are optional, depending on the study. The details of the tasks and how they should be carried out are not included, but reference is made to the relevant sections of this chapter where recommendations can be found.

- Collate the available hydrological data for gauging stations in the vicinity of the BBM sites (Sections 12.3 & 12.4.1).

- Attend the Planning Meeting (Section 6.6) and provide information on the quality of the available hydrological data, and on the methods that will be used to generate daily time series of streamflow and flood event information (Section 12.3).
- Generate present-day and natural daily hydrological data for the sites, and summarise the main characteristics of the flow regimes in the hydrology section of the starter document (Sections 12.4.2, 12.4.3 & 12.5).
- Establish the daily time series as data files that can be used at the BBM Workshop with suitable display and analysis software (Section 12.4.4).
- Attend the workshop and assist the other specialists in the interpretation of the hydrological data (Section 12.6).
- Calibrate the IFR Model to satisfactorily reflect the modified flow regime recommended by the other specialists at the workshop. Monthly summaries of the design EFR releases should then be made available to the design engineers (optional: Sections 12.4.4, 12.6 & 12.7.1).
- Set up the DAMIFR Model and necessary data files, in preparation for Scenario Meetings (optional*:* Sections 12.4.4 & 12.7.2).
- Attend the Scenario Meetings to assist with interpretation of the hydrological data and release requirement data. Run various water supply/release scenarios through the DAMIFR Model, as required (optional: Section 12.7.2).
- Advise on any monitoring actions required with respect to hydrology (optional*:* Section 12.12).

12.9 MINIMUM AND OPTIMUM SPECIALIST TRAINING

The training required to operate as the hydrological specialist for an assessment using the BBM largely depends upon the methods that will be used to generate the data. If these methods are relatively simple (i.e. no modelling), then the main skills required are the ability to understand and explain the characteristics of a river's flow regime using a range of analytical approaches for summarising daily flow time series. It is also essential that the hydrologist has access to suitable time series analysis and display software and can operate this with confidence. If daily flow sequences are not readily available, then additional skills are required to generate these through simulation or extrapolation techniques. If the hydrologist has a sound background understanding of the way in which a river's flow regime impacts on the other processes, he/she will be able to respond efficiently to requests for information from the other specialists. A deep appreciation of what the other specialists are trying to achieve is important.

12.10 POTENTIAL PITFALLS

One of the major potential pitfalls relates to the fact that the hydrologist is providing service information, and the hydrological functioning of the river has little direct importance in the BBM process. It is thus all too easy for the hydrologist to become detached from the objectives of the assessment, and not to keep track of whether the modified flow regime being compiled makes hydrological sense.

The specialists carrying out the design of the water-resource scheme and the yield analysis will be hydrologists, and could be the same group used to prepare the BBM hydrological data. The potential problem here is that the BBM application has to proceed independently of the likely future offstream demands on the river, and so the hydrologists should not introduce a bias due to being involved in both design processes. Conversely, when two different groups are involved in these activities, they could potentially use different methods of generating hydrological data, resulting in incompatible results. The solution to this latter scenario is to ensure that the two groups liaise at an early stage in both design processes (i.e. the storage/yield design and the EFR design).

A further pitfall is that the budgets for preparing the BBM hydrological data are often limited, and there is a danger that over-simplistic approaches will be used and unreliable results generated. The following section addresses this issue further.

12.11 FURTHER DEVELOPMENTS

Any developments that improve the accuracy and reliability of methods to estimate the regime characteristics of rivers at ungauged sites will benefit application of the BBM. Similarly, developments in the efficiency of application of these methods, and of the approaches to analysing and displaying the information will also be of value, particularly given the limited budgets that are frequently available for EFAs. Recent developments in hydrological modelling have tended to concentrate on generating the most reliable results, and so some recent models are ‘information hungry’ and largely inappropriate for use in the BBM, because of time, budget and information constraints. There is certainly scope for further research into pragmatic approaches to generating reliably representative natural flow regimes.

12.12 MONITORING

There are two main areas where post-development monitoring could be important from a hydrological point of view. The first is in situations where there is no suitable gauge close to a critical BBM site, but it is considered necessary to monitor the extent to which the EFR flows are being met by releases from a reservoir. If the reservoir is close to the site, this will be largely unnecessary as it can be assumed that the releases will reach the site unmodified. However, where significant and unmeasured tributary inflows, or natural and artificial abstraction losses occur, monitoring of river flow may be required. Whether such monitoring occurs at a formal gauging station (using a structure or rated section), or at a point at which occasional observations of flow rates are taken, depends upon the resources available to the agency responsible for the monitoring programme.

A second area of monitoring relates to the patterns (spatial and temporal) of losses between the flow control structure and the BBM sites. It is necessary to establish a monitoring programme that will update this information periodically, to ensure that the designed flow releases are sufficient to satisfy the identified offstream demands as well as the EFR (ecological Reserve). While there is some overlap here with the first requirement for monitoring, this latter activity is still required in order to maintain a complete understanding of the dynamics of the river system. The extent to which a programme of monitoring abstractions will be successful depends largely upon the legislation relating to water use and the effectiveness of any policing practices.

12.13 CONCLUSIONS

There are many uncertainties inherent in the BBM process. These are largely a result of the difficulties of understanding the complex interactions between the biotic and abiotic environments of rivers. An important part of the preparation for a BBM Workshop is the need to decrease the amount of uncertainty, in any component of the methodology, as far as possible. It is therefore essential that the best and most reliable methods be used to prepare the hydrological information. The other overriding factor is that this information should be presented to the other specialists in a form that they are familiar with or can readily understand. While this does not exclude new and innovative approaches to analysing and presenting the hydrological data, it does emphasise the advantages of some measure of standardisation of approach across various applications of the BBM. If the non-hydrologists are continually confronted with different ways of presenting the material, they are unlikely to develop the necessary intuitive understanding of hydrological data that they require, in order to properly understand the links to their own area of specialisation.

13. HYDRAULICS

Bill Rowlston, Angelina Jordanova and Andrew Birkhead

13.1 LOCAL HYDRAULICS IN THE ECOLOGICAL FUNCTIONING OF A RIVER

The flow of water in a river channel and the physical structure of the channel are intimately related in a cycle of cause and effect in space and time. Depending on the susceptibility of the channel to flow-related change, its morphology is determined by local geology as well as by the sediment and flow regimes, whilst local hydraulic conditions are determined by the geometry and flow resistance of the channel. Local hydraulics and channel morphology are the primary determinants of the availability of physical habitat which, in turn, is a major determinant of ecosystem functioning.

A quantitative understanding of a river's flow regime, its physical structure, and its depth/velocity regime, derived jointly and severally from hydrological, geomorphological and hydraulic analyses, is therefore a prerequisite for deriving quantitative information about its ecological functioning.

13.2 HYDRAULIC STUDIES IN THE BUILDING BLOCK METHODOLOGY

Researchers into EFRs for rivers tend to quantify the water needs of the various biotic components in terms of parameters such as water depth, flow velocity, wetted perimeter and water surface width. Time is added as a parameter, by referring to the frequency of occurrence of a particular discharge, or the duration of inundation resulting from a particular flooding event. Duration, depth and lateral extent of inundation are especially relevant when considering the water requirements of riparian biotas.

Hydrologists, water engineers and water resource managers, on the other hand, are more used to dealing with the water needs of humankind and habitually express these needs in terms of volume of water linked to time. The units of measurement used can range from instantaneous discharge expressed in cubic metres per second ($m^3\,s^{-1}$), to long-term requirements in millions of cubic metres per annum ($Mm^3\,a^{-1}$).

Both approaches are completely valid in their own context, but the application of the BBM requires an interface between them. This interface is found through the hydraulic analysis of flow in natural open channels. The results of hydraulic analysis and modelling therefore form the essential link between the way in which water managers express the flow of water in the river, and the way in which river scientists express the water requirements for the river system itself.

The product of the hydraulic component of the BBM comprises a series of relationships between discharge and, among other parameters, water depth, flow velocity, wetted perimeter and water surface width. Fluvial geomorphologists and aquatic ecologists use this information to quantify flow requirements for the river in ways which are described in other parts of this manual. The specialist in aquatic invertebrates, for example, considers the availability of hydraulic habitat for the river's characteristic invertebrate communities and how this might change with changes in discharge (Chapter 17). Fish biologists may take into account the requirement for a critical depth or velocity for fish passage, or for the inundation of particular habitats, particularly for breeding, and for refuge areas in low flow conditions (Chapter 18). Vegetation specialists draw on information about the flooding requirements for recruitment of key species of riparian trees and marginal vegetation, and the effects of geomorphological changes on the extent, for example, of reed beds (Chapter 16). The geomorphologist requires an estimate of the hydraulic shear stress, in order to determine the flow at which various sediment sizes may be entrained (mobilised), transported and deposited (Chapter 14). Additionally, consideration of the flows required for channel maintenance might be based on knowledge of the water levels (stages) necessary for inundation of particular morphological units such as terraces and benches.

It is important to note that there is great emphasis in the BBM on the hydraulic characterisation of low flows, because these are the flows that are experienced by the biota for the majority of the time. It is also necessary to understand how the riverine ecosystem is likely to change as discharges are reduced as a result, for instance, of increasing abstractions. The difficulties attendant on modelling low flows - compared with the analyses of high flows and floods that are more familiar to engineering hydraulicians - are not to be underestimated, and are revisited throughout this chapter.

Except for the special case of sediment as a component of water quality, and its transport or deposition in a river channel, hydraulics as discussed in this chapter does not specifically deal with water quality considerations. Water quality modelling is, however, dependent on the hydraulic characterisation of a river to provide information on, for instance, current speeds, retention times and mixing conditions (Chapter 15).

13.3 SEQUENCE OF ACTIVITIES

13.3.1 Site selection and placement of cross-sections

The selection of sites for consideration in an application of the BBM is dealt with in detail in Chapter 7, from which it is clear that a wide range of factors is taken into account.

As the principal purpose of applying the BBM is to determine the flow regime that will maintain the river at a predetermined EMC, biotic considerations will dominate the selection of appropriate sites. Resource constraints will almost always dictate that the study area has to be characterised by a relatively small number of BBM sites. This in turn dictates that the limited number of sites used should illustrate as high a degree of diversity of physical habitat, and therefore biota, as possible. Consequently, thus far in the relatively brief history of EFAs using the BBM in South Africa, sites that include riffles have been most widely used. Riffles are hydraulically complex, especially at the low flows that receive most attention in EFR determinations, and are more sensitive to changes in flow than almost any other channel feature. During low flows, water depth in riffles is usually the same order of magnitude as the roughness elements (cobbles and boulders) which comprise the riverbed, resulting in wide variations and non-uniformity of flow velocities. These factors complicate the hydraulic analysis.

As a result of the emphasis in BBM assessments on biotic habitat, the hydraulics specialist should not expect hydraulic considerations to enjoy absolute pre-eminence in site selection. However, it is equally important for the hydraulician to influence the selection process to the extent that the sites chosen are not of such hydraulic complexity that reliable hydraulic analysis becomes impractical. A site that is difficult to analyse will almost certainly produce hydraulic information that is of low confidence, with consequent negative implications for the rest of the process. An example of a difficult site is one characterised by multiple distributary channels flowing at different water levels.

The hydraulic complexity of the sites selected for a BBM application has a profound influence on the ways in which hydraulic data are analysed, particularly in respect of the proportions of observed and modelled data required for the production of reliable relationships between discharge and, for instance, depth and velocity. As a general rule, the more hydraulically complex the site, the greater the reliance on observed data for reliable results from the hydraulic analysis. Conversely, the hydraulic characterisation of a simpler site may be achieved by using relatively sparse observed data, followed by the use of appropriate hydraulic modelling techniques.

Once the BBM site has been selected, it is important that adequate time and effort are assigned to the selection of cross-sections, and that all specialists are involved. The hydraulic characterisation of the site - and therefore the characterisation of its physical habitat - is primarily confined to the cross-sections, and therefore the success of the process is largely dependent on these being located in a way that adequately describes all features of interest for any of the specialists.

Although a BBM site is three-dimensional, spatially linked two-dimensional cross-sections are used to describe both the river geometry and the relationships between discharge and the hydraulic determinants mentioned previously. Methods are currently being investigated for extending the hydraulic characterisation to provide a more representative spatial description of the sites, without the need for full, three-dimensional topographical surveys and hydraulic modelling (Section 13.11). It is the responsibility of the hydraulics specialist to determine the number and location of channel cross-sections required to characterise the site hydraulically. It is difficult to predefine the number of such cross-sections required, since this is affected by both the local biotic and abiotic characteristics. Experience has shown that the following approach is appropriate for a potentially difficult and time consuming task:

- each specialist present at the site selection exercise locates and justifies his/her choice of ‘non-hydraulic’ cross-sections;
- the positions and importance of all these cross-sections are considered by the full team, to assess if cross-sections can be combined without loss of essential information;
- additional cross-sections for hydraulic purposes (positioned at changes in water slope and channel geometry) are identified by the hydraulician, and the purpose of their inclusion is explained to the other specialists.

When selecting the additional hydraulic sections, the hydraulician should bear in mind that hydraulic controls (i.e. determinants of the relationship between discharge and water depth) are a function of discharge. The additional sections should therefore be selected at a discharge appropriate to BBM-type applications; that is, with greater emphasis on low flows.

An important consideration in site selection is the ease (or otherwise) with which the discharge through the site may be measured or calculated (Section 13.3.3). Discharge through a rapid or riffle is relatively difficult to measure directly with any confidence. Therefore, before selecting a cross-section through such a channel feature for direct, manual gauging, it is necessary to consider whether discharge could be more reliably measured at a different, nearby cross-section, either within or just outside the BBM site. A suitable cross-section should be prismatic, have materially uniform flow (i.e. flow that does not change with distance along the river), and have water that is considerably (say, ten times) deeper than the roughness elements constituting the bed. If outside the site, this surrogate discharge cross-section should be sufficiently close to it that any losses or inflows between the two are minor and can safely be ignored. If the need arises for such a surrogate cross-section, its position should be clearly identified, so that it can be used on each occasion when discharge is measured. It should also be surveyed relative to a fixed datum, as are all BBM cross-sections.

13.3.2 Site surveys

The main purpose of the survey at a BBM site from the hydraulics viewpoint is to define the cross-sectional profile of the river channel in sufficient detail to enable hydraulic measurements, modelling and analysis to be undertaken at the required levels of resolution. A second priority is to describe on these profiles the location of features of interest to river scientists, which may then be portrayed on the site plan and on plots of the channel cross-sections. Requirements in this respect should be obtained from the relevant specialists.

The survey should extend from bank to bank of the macro-channel, and should incorporate all significant changes in slope and substratum type along the profile. Roughness elements along the profile that are frequently transported (i.e. annually) constitute the overall resistance of the river channel, and therefore need not be surveyed in minute detail. Larger sedimentary obstructions that are moved infrequently, however, should be included in the cross-sectional survey, since these features reduce the channel area for all but the highest floods.

At least two permanent benchmarks should be placed at each of the cross-sections and clearly marked for future identification. One benchmark should be established at each end of the cross-section if its orientation needs to be obvious to those working on site. The benchmarks form the local datum for linking the plan orientation, the elevation data on the cross-sections, and the longitudinal riverbed and water surface profiles. It is therefore essential that they be related to each other in elevation to an acceptable degree of accuracy (±1 cm), particularly for sites characterised by mild water surface slopes.

It is preferable to survey the defined channel cross-sections at the outset of the BBM study during low flow conditions. It may, however, be necessary to select sites when higher flow conditions prevail, due to untimely climatic conditions, or because the site selection trip has to take place during the wet season. Under such circumstances, stage-level data (and discharge data, discussed in Section 13.3.3) may be collected along the longitudinal river profile and reconciled with the positioning of cross-sections at a later date. If, during the course of the BBM exercise, a high flow event occurs which causes cross-sections to change (through scour of bed or banks, or deposition of sediments), it will be necessary to resurvey the channel. Significant changes in cross-sections will necessitate a re-evaluation of work undertaken previously, and may invalidate some of the results. Although it is difficult to directly include provision for such eventualities in the work programme, implications in terms of additional resources and changes to the scheduling of the overall study should be addressed in the work outline.

Stage-discharge relationships should be developed for each cross-section. Therefore, at every site visit when the discharge is measured, water levels relative to the local benchmarks should be surveyed at the edges of each active channel along the cross-sectional profiles. At sites where access into the river is safe, longitudinal riverbed and water surface profiles should also be surveyed along the lowest point in the channel (thalweg), extending approximately ten channel widths beyond the downstream and upstream cross-sections. These data on longitudinal water surface profiles are particularly necessary when resource constraints dictate that a single cross-section is used to characterise a site, because the longitudinal slope is needed for modelling purposes.

Whilst recording bed and water levels along the longitudinal profile, the opportunity should also be taken to record depth-averaged velocities at the lowest bed level. The use of these data in the overall process is, as yet, not fully defined, but in the few cases where such data have been gathered it has helped fish and aquatic invertebrate specialists develop a more three-dimensional picture of the way in which velocities vary along the river.

The equipment best suited to undertaking the survey is a total station linked to a data logger, with the data recorded in an unreduced (raw) format (i.e. horizontal and vertical angles, and distance) and not as reduced coordinates. The survey data may then readily be reduced using trigonometric principles to produce cross-sectional profiles, plan orientation of sections, stage levels and longitudinal profiles.

Some hydraulicians may have sufficient expertise, and the necessary equipment, to carry out the survey. Alternatively, experienced surveyors may be employed for the task. In this latter case, experience has shown that useful results are obtained only if the surveyors know and understand the purpose of the work, and the reasons for the details they are asked to record. Irrespective of who actually carries out the survey work, the hydraulician is responsible for defining the level of detail required in the survey.

It should be self-evident that survey work should be carried out at the actual BBM sites. However, hydraulic analysis of flood flows, with which engineering hydraulicians are generally more familiar, is often possible to an acceptable degree of accuracy with data derived from contour plans, orthophotographs, and aerial and terrestrial photographs. This is definitely not the case when dealing with the low flows which are so important in BBM determinations, where the necessary detail can only be acquired through measurements taken at the sites.

The importance of visual information on the sites cannot be overemphasised, and every opportunity should be taken to photograph the widest possible range of discharges. Surprisingly accurate quantitative information about incremental changes in width and depth can often be derived from photographs, by relating flow levels to known features on the cross-sections, such as a prominent large boulder, or to the extent of inundation of marginal vegetation.

At each visit to each site, at least three photographs of each cross-section should be taken, each from a subsequently identifiable and repeatable fixed point: across the channel along a surveyed cross-section; and upstream and downstream of the same cross-section. Photographs should be linked to a known discharge, and dated.

Visits to sites for the collection of hydraulic data are often more frequent than for the other specialist disciplines. At the outset, the hydraulician should obtain from the other specialists their requirements, if any, for regular photographic records, and build these needs into the programme of site activities at each visit.

13.3.3 Measurement of discharge

To be of any use in an application of the BBM, parameters such as water depth and velocity that are of interest to the other specialists have to be related to a known discharge. Various methods exist for the measurement of discharge, including the use of existing rated sites (natural river sections or structural gauges), and manual techniques such as the velocity-area or dilution methods. A gauging weir or rated cross-section located in close proximity to the BBM site provides a useful means of obtaining discharge data. The integrity of data derived from such stations, however, should not be taken for granted, but rather checked with the authority responsible for its operation. The gauge should be sufficiently close to the site that intervening inflows and losses may be ignored. Furthermore, care should be exercised during unsteady flow conditions, that is, when discharge is increasing or falling, to account for the travel time and attenuation of flow between the site and the gauging point. A method for synthesising rating relationships, based on the measurement of an unsteady flow event, is provided by Birkhead & James (1998).

The velocity-area method is undoubtedly the most commonly applied manual technique for measuring the discharge in natural, medium to large watercourses. On the other hand, dilution techniques are better suited to turbulent rivers, such as a rock-strewn river of high bed slope, where other methods are difficult to apply. Details and standards for the application of these manual gauging techniques are given in the British Standard for the Measurement of Liquid Flow in Open Channels (British Standards (BS) 3680 1980, 1983), which should be consulted to ensure correct application of the methods. Gordon *et al.* (1992) also give easily understood descriptions.

Point velocities recorded during manual discharge measurements also describe the distribution of velocity across the channel and, if water depth is great enough at any point for more than one reading to be needed to estimate depth-averaged velocity, vertically in the water column. The hydraulician should ascertain if these velocity data are of use to any of the other specialists, notably the fish biologist and the fluvial geomorphologist. This topic is dealt with further in Section 13.11.

In order to observe as wide a range of discharges as possible, it is highly desirable to undertake discharge and related measurements, by whatever method, over at least one hydrological season. However, this does not necessarily guarantee that a suitable range of flows will be encountered, because of the possibility of unfavourable climatic conditions such as a failed wet season or unseasonably high flows in the dry season. Under such exceptional circumstances, the BBM Workshop may have to be postponed or, if this is not possible, additional data collection and refinement of the hydraulics and environmental flow recommendations will be required following the workshop.

Measuring discharge by direct methods during high flows, where depth and velocity of flow may militate against safely entering the water, requires the use of boats or other techniques, and demands high standards of safety to avoid accidents. Dangers from the natural inhabitants of the river such as hippopotami and crocodiles, and the risk of contracting river-related diseases such as bilharzia, should also be taken into account.

When high flows make entry into the river inadvisable, stage levels at the banks should be recorded at the cross-sections as well as upstream and downstream of the sections, as discussed in Section 13.3.2. Where possible, floating objects should be used to measure surface velocities. The use of surface velocities to obtain an estimate of discharge is described in BS 3680 (1980, 1983).

13.3.4 Data analysis and modelling

Observed cross-sectional and flow data, the latter often for a limited range of discharges, is used to establish relationships between discharge and hydraulic parameters of interest to the river scientists. These relationships will almost certainly have to be described for a greater range of discharges than the observed range.

When sufficient observed rating data exist it is possible to establish rating functions based entirely on field measurements, by fitting relationships of the form given by Birkhead & James (1998) to the observed data (Figure 13.1). Care should be exercised with the extrapolation of the modelled relationship beyond the highest and lowest recorded discharges. The validity of the extrapolation can be assessed by computing inferred resistance coefficients and average velocities beyond the range of observed data, and comparing these with reasonable values based on experience and on resistance coefficients given in the literature (Chow 1959; Henderson 1966; Barnes 1967; Hicks & Mason 1991).

Synthesis of a rating relationship essentially involves interpolation between sparse data points, and extrapolation beyond the limits of observed data. Flow resistance in natural watercourses, and therefore the resistance coefficient used in the analysis, is generally a function of stage, particularly at low stages. The rating relationship may therefore be synthesised by calculating resistance coefficients at the observed data points, then interpolating and extrapolating to derive resistance coefficients between observed data points and beyond the limits of observed data, respectively. The selection of a suitable resistance relationship and corresponding coefficient (e.g. Darcy-Weisbach's f - dimensionless, Chézy's C - $m^{1/2}/s$, or Manning's n - $s/m^{1/3}$) is considered arbitrary in the existing application. Rather, selection should be based on pragmatic considerations such as, for example, the resistance equation applied in the software to be used, experience and familiarity. This is because, although certain relationships are theoretically more rigorous than others, it is illogical to apply the most rigorous modelling approach in a situation where the resistance coefficient is essentially a 'composite' calibration factor based on field data. This factor and the energy losses cannot be derived solely from consideration of the measurable physical dimensions of the resistance components (e.g. size of the roughness elements, vegetation type and density, channel plan form). Extrapolated rating relationships may be developed by extrapolating the resistance coefficient based on calibrated data (i.e. fitting a relationship to the resistance coefficient versus discharge (or stage) data and extrapolating). Calibrated resistance coefficients are usually determined based on non-uniform flow profile computations (i.e. backwaters), or by assuming linear variation of the energy slope for a site represented by a single cross-section. Once again, care should be taken, by judicially assessing the values of the extrapolated coefficient and comparing these with values based on experience and the published literature.

A major difficulty with low flow hydraulic analysis of many cross-sections that describe deeper pool-like parts of the channel, is the estimation of the stage of zero discharge, that is, the water level in the pool when flow ceases. This relationship is needed when modelling flow of water through the site as a whole. In the absence of observed data, the most appropriate method for estimating the stage of zero discharge is to survey the longitudinal profile downstream of the cross-section, along the deepest portion of the active channel. This will reveal the level of the downstream bed that causes the upstream backup, which can then be accepted as the stage of zero discharge for the pool-like stretch. Alternatively, extrapolation of the observed rating data to zero discharge may also provide a useful, albeit approximate, estimate of the stage of zero discharge.

Once the rating relationship for a cross-section has been developed, the relationships between discharge and other hydraulic determinants (e.g. average velocity, wetted perimeter and average depth: Figure 13.2) may readily be computed using knowledge of the cross-sectional geometry.

Hydraulic analysis and modelling should only be carried out by skilled practitioners who are familiar with low flow techniques and problems, as the errors inherent in applying the traditional approaches suited to high flows resonate through the entire process. For instance, the values of the resistance coefficient, Manning's *n*, which must be applied to low flows in a riffle, are considerably higher than the range of values used in high flow analyses. Application of inappropriately low *n* values results in significant underestimation of water depths, and therefore overestimation of velocities, for specific discharges. This in turn prompts overestimation of the discharge needed to achieve a particular water depth for, for instance, fish passage, and thereby inflates the EFR.

13.4 MINIMUM AND IDEAL DATA SETS

13.4.1 Site selection and surveys

It is absolutely essential for the hydraulics specialist to visit, inspect and photograph prospective sites, and to carry out or oversee the site survey. As emphasised previously, it is completely impractical, when contributing to a process that will be advising on low flows for river maintenance, to work from contour maps or contoured site plans alone.

The accuracy of the surveys of cross-sectional profiles and water levels should be comparable to the level of accuracy with which results are presented in the starter document and at the BBM Workshop. For example, it is fallacious to predict changes in discharge due to 1 cm variations in river stage when water levels are accurate to, say, only 5 cm.

13.4.2 Stage-discharge relationships

In general, the more available data on observed stages versus discharge, the higher the confidence in the derived hydraulic relationships. Every possible opportunity should therefore be taken to visit the sites and gather such data from every surveyed cross-section.

Sites characterised by a prismatic channel shape and uniform flow conditions require relatively fewer observed data on stage and discharge than more complex sites containing rapids or riffles, since the hydraulic relationships for the former are relatively easier to synthesise analytically.

Ideally, measurements should be taken at significantly different discharges. The discharge range 0-5 $m^3 s^{-1}$ is better characterised by measurements at 0.2, 0.5, 1.2 and 5 $m^3 s^{-1}$, than by ones at 0.1, 0.12, 0.15 and 5 $m^3 s^{-1}$. This requires careful planning of site visits to maximise the likelihood of procuring an appropriate range of discharges. The appropriate range is river-dependent, and a function of how much each increment of flow influences water depth. When extrapolating the observed low flow data, some flood-related information may be useful for fixing a high point of the stage-discharge curve. This can sometimes be derived from recording the level of flood-borne debris on the river banks or in trees, or from information obtained from residents living close to the river, and relating this to known flows in the hydrological record.

- An **absolute minimum** data set would be one stage measurement at an appropriate low flow, plus the stage of zero discharge.
- An **acceptable** data set would be three such stage measurements distributed over the low flow range of interest, plus the stage of zero discharge and some flood-related data.
- An **ideal** data set would be six data points over a good distribution of discharges, plus the stage of zero discharge and some flood-related data.

13.5 STARTER DOCUMENTATION FOR THE WORKSHOP

The following is a list of what is required in the starter document.

- A brief summary of the method used to determine the rating relationships.
- A record of techniques used to collect discharge data.
- Tabulated observed data on discharge versus water depth, and resistance coefficients.
- Plots of the rating relationships, using a log-normal scale. These should show the observed data, and the cross-sections (Figure 13.1), for low, intermediate and high discharge ranges.
- Plots of discharge against water depth (maximum and average), average velocity and wetted perimeter (Figure 13.2) on normal scale axes.
- An explicit estimate of the accuracy in the rating relationships over the range of observed data. This may be produced by calculating the average absolute difference in water depth or discharge between the observed and modelled data.
- An assessment of the confidence in the extrapolated rating relationships.

13.6 ROLES AND RESPONSIBILITIES AT THE WORKSHOP

- Explanation of data and information presented.
- Interpretation of data and assistance to other specialists in deriving useful and appropriate information from the hydraulic data, using computerised graphical displays of cross-sections where available.
- Assessment of levels of confidence in the hydraulic data.
- Assessment of the limitations of the data.
- Transfer of technology.

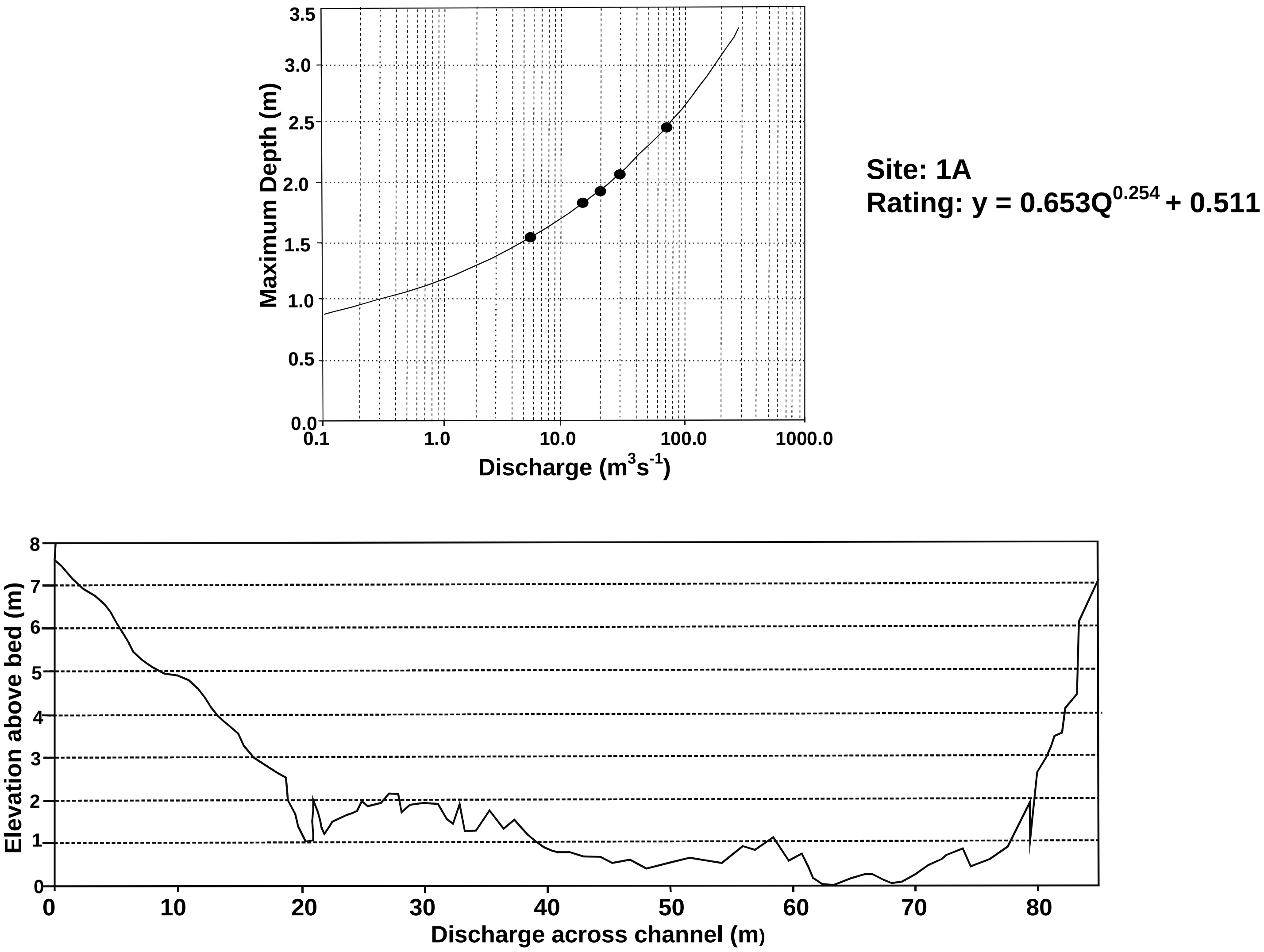


Figure 13.1 Example plots of the rating relationship (log-normal scale) and cross-sectional profile for a cross-section (A) at a typical BBM site (site 1).

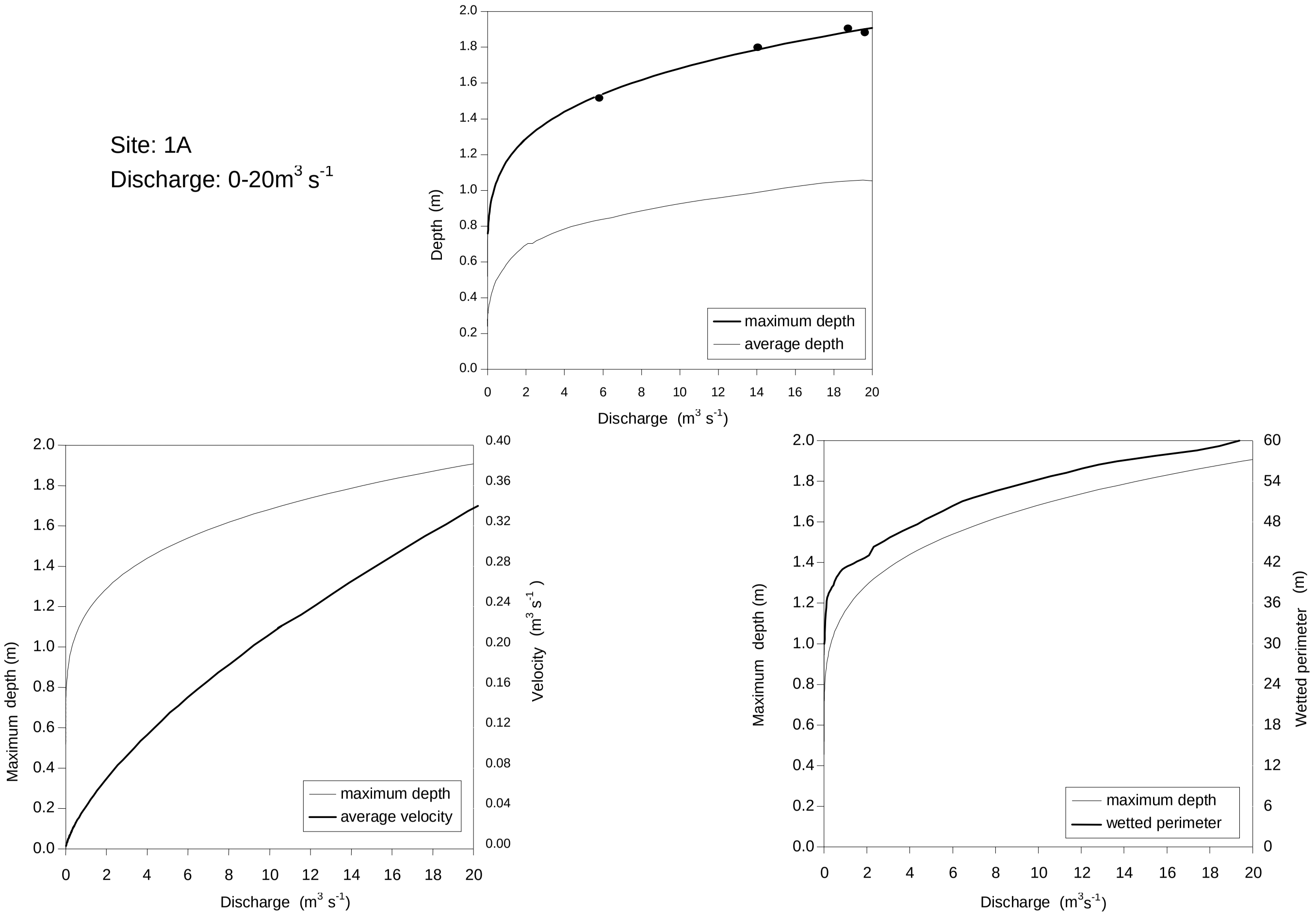


Figure 13.2 **Example plots of water depth (maximum and average), average velocity and wetted perimeter against discharge, over the range 0-20 m^3 s^{-1} for a cross-section (A) at a typical BBM site (site 1).**

13.7 ROLES AND RESPONSIBILITIES AFTER THE WORKSHOP

A large part of the credibility of the BBM process lies with the quality and reliability of the hydraulic information. The fundamental importance of reliable hydraulic information to the work of the other specialists involved in the assessment demands that results of the highest possible quality, in terms of completeness and confidence, be presented to them. Shortcomings in the hydraulic information will usually militate against a successful EFA, and it should never deliberately be assumed that hydraulic inadequacies can be made good at some later stage. If the standard of the hydraulic work is not high prior to the workshop, then additional surveying and modelling will be required afterwards. This is neither efficient nor cost-effective.

Hydraulic work in connection with monitoring the efficacy of the specified EFR in achieving the selected EMC is discussed in Section 13.12.

13.8 EXAMPLE OF TERMS OF REFERENCE

The Terms of Reference for the hydraulics specialist have been referred to previously, in the descriptions of the tasks necessary to carry out the study. In addition, however, the Terms of Reference should provide an explicit breakdown of the allocation of resources (time and rate of remuneration) for the essential tasks, including:

- site selection;
- river channel cross-sectional and longitudinal profile surveys;
- field trips for collection of hydraulic data;
- reduction of survey and hydraulic data;
- hydraulic analysis and modelling;
- reporting;
- BBM Workshop;
- post-workshop activities, such as additional data collection and refinement, monitoring and Scenario Meetings.

Allowance should be made for an assistant to aid in the collection of survey and hydraulic data. The minimum time required for collection of hydraulics data is half a day per site. A more reasonable allocation would be one day per site, in order to complete all of the tasks described in this document.

13.9 MINIMUM AND OPTIMUM SPECIALIST TRAINING

If the hydraulics data are to successfully support the work of the other specialists, all of their aspects - site selection, site survey, discharge measurement and the analysis of hydraulic data - require a high degree of specialist knowledge, expertise and experience. Expertise in low flow analyses is essential.

Local, non-specialist assistance can be enlisted, however, for gathering water level and discharge data, and maintaining the photographic record. Such assistance could provide additional observed data points, whilst reducing the number of site visits that the hydraulician has to make. Extreme care should be taken with the selection and training of such assistants, since experience has shown that intelligent, interested people still may have little conception of the importance of a structured, careful record of events.

To illustrate, one such attempt was made with the staff of a nature reserve. They agreed to observe and record relevant stage and associated data for the river in their reserve, as this did not have an automatic device for measuring discharge. The intention was to supplement a limited number of on-site observations made by specialists living far from the river, in order to obtain a record of flow-related events through the complete annual hydrological cycle. Although considerable efforts were made to define the necessary sequence of tasks, both verbally on site, and in writing using simple illustrations, the resulting data were virtually useless for augmenting data gathered by the specialists. This was by no means due to lack of intelligence on the part of the people involved, who were well-educated environmentalists, nor from a lack of understanding of the objectives of the exercise, but arose from an understandable unfamiliarity with the hydraulic concepts involved. Such attempts to enlist outside help should not be made lightly, nor should great reliance be placed on the results.

13.10 POTENTIAL PITFALLS

The potential pitfalls have been discussed in the relevant sections of this document, with the following concerns deserving re-emphasis:

- inappropriate location of cross-sections (biological and hydraulic);
- surveys undertaken in insufficient detail and not linked to a common datum;
- inability to re-locate fixed benchmarks;
- inaccurate stage and discharge measurements;
- insufficient data over a limited flow range;
- inappropriate hydraulic analyses, particularly for low flows.

13.11 FURTHER DEVELOPMENTS

As discussed in Section 13.3.1, spatially linked two-dimensional cross-sections are used to describe the river geometry and the relationships between discharge and various hydraulic determinants. Consequently, the determination of the EFR is strongly focused on the geometry of two-dimensional river cross-sections. In order to provide a less spatially-fixed description of the site, Birkhead (1998) provided flow-related depth data as frequency distributions of available depths across the cross-sections.

Similar analyses of the distributions of depth-averaged velocities would provide useful information for invertebrate and fish ecologists. It would be advisable to produce this only from measured velocity data, due to the difficulty of simulating velocity distributions across non-prismatic channel cross-sections. To further develop the role of hydraulics in the BBM, it would therefore be necessary to invest the time required to collect these data.

The application of full three-dimensional modelling techniques in order to obtain an improved characterisation of the hydraulic conditions across the sites is prohibitive, primarily in terms of the data collection requirements for a BBM-type analysis. There is potential, however, to extend the existing hydraulic modelling exercise, to provide data on habitat availability in quasi three-dimensions. This can be done by integrating longitudinal hydraulic characterisation of the site with cross-sectional characterisation, and by additionally compiling habitat maps of the site with accompanying hydraulic statistics (e.g. see Brown & King 1999). Broadly, habitat mapping provides a plan description of the habitat conditions at the site, and the longitudinal hydraulic analysis provides a continuous water surface profile between cross-sections. Consequently, it is possible to model in a very coarse fashion (based on the water surface profile as datum), the changes in water depth and velocity of the complete mapped areas.

13.12 MONITORING

The overall objective of the monitoring exercise is to assess the effectiveness of the specified EFR in achieving and maintaining the desired EMC. Two phases are envisaged: establishment of baseline conditions, followed by monitoring to detect changes in the baseline conditions.

Ideally the baseline conditions, defining the hydraulic characteristics of all the sites for a full range of flows, should have been determined prior to the BBM Workshop. If this was not possible in sufficient detail, baseline monitoring should include collection of additional data to complete such an hydraulic characterisation. There could be a need for supplementary observations to augment an incomplete flow range, or repeat observations to raise confidence in a data set questioned in the workshop. If very high flows occur subsequent to the workshop and are believed to have altered the morphology of the channel, and consequently a site’s hydraulic characteristics, a re-survey of cross-sections, followed by a repeat comprehensive hydraulic analysis, will be required to establish a new baseline condition.

Long-term monitoring involves repeat visits (regular, and also after high flow events) to the sites, to re-survey the cross-sections. This monitoring aspect should be designed to allow detection of flow-related morphological changes and to collect flow-related data, followed by re-evaluation of the hydraulic relationships.

Hydraulic monitoring relates closely to hydrological monitoring, the aim of which is to determine the degree of concurrence between the flow regime eventually decided upon by the water manager and that which actually occurs.

13.13 CONCLUSIONS

Experience with EFAs for South African rivers has repeatedly shown that the availability of reliable hydraulic information is of quintessential importance to the success of the process as a whole. If biologically relevant data in terms of depths and velocities of flow cannot be related to discharges, the EFR cannot be quantified. Although the work required to gather and analyse hydraulic data can be costly and time consuming, especially in rivers in remote areas or where access is difficult, the investment pays rich dividends in terms of confidence in the output from an application of the BBM. It is infinitely preferable to undertake this work prior to the BBM Workshop, where it can be confidently used by the other disciplines, rather than to enter the workshop with inadequate or low confidence information. The latter situation wastes the participants' time, and usually subsequently leads to the entire procedure having to be revisited with improved hydraulic information.

If no reliable hydraulics data are available, no reliable assessment of EFRs can be undertaken.

14. GEOMORPHOLOGY

Kate Rowntree

14.1 GEOMORPHOLOGY IN THE STRUCTURE, FUNCTIONING AND MANAGEMENT OF RIVERINE ECOSYSTEMS

Fluvial geomorphology is the scientific study of the origins of landforms caused by flowing water. It has as its focus the channel form resulting from erosion and deposition forces. These occur both within the channel and in the associated riparian zone. Geomorphological processes therefore play an important role in determining the structure and functioning of riverine ecosystems. Channel shape is particularly significant in determining the quality and availability of physical habitat, through its effect on such variables as local hydraulics and the proportions and distributions of different sized substrata.

14.1.1 Theoretical background

The significance of geomorphological variables that need consideration in EFAs is summarised in Table 14.1. Three groups of criteria have been identified: the spatial and temporal availability of physical habitat, the maintenance of substratum characteristics, and the maintenance of channel form. These three groups differ in terms of the spatial and temporal resolutions at which they should be addressed.

Table 14.1. A geomorphological framework for the assessment of EFRs: criteria and information needs (modified from Rowntree & Wadeson 1997).

CRITERIA	TIME SCALE	SPATIAL SCALE	INFORMATION NEEDS
Spatial and temporal availability of physical habitat.	Short term (<1-5 years)	Hydraulic biotope and morphological unit (<1-10 m^2)	Distribution of hydraulic biotopes; channel cross-sections; substratum type; floodplain morphology.
Maintenance of substratum characteristics:			Particle size distribution; cross-section hydraulic geometry; channel gradient; rate of sediment supply from upstream.
Seasonal flushing of substratum.	Short term (<1-5 years)	Morphological unit (10-100 m^2)	
Modification to substratum.	Medium term (2-20 years)		
Maintenance of channel form:			
Adjustment of channel plan and cross-section.	Long term (10-100 years)	Reach (100 m)	Channel cross-sections; channel gradients; bed and bank resistance to flow; sediment supply; natural flow regime.

The most immediate problem addressed by ecologists determining an EFR is the change in available physical habitat for selected species, caused by changes in the flow regime imposed on the channel. Among the physical criteria recognised as determining habitat are flow characteristics such as water depth, velocity and associated hydraulic indices, and substratum characteristics. These criteria are functions of channel morphology, and hence are directly related to the spatial variability of geomorphological processes. Available habitat is site-specific and species-specific, and ascertaining its nature and extent requires detailed surveys of the channel morphology at sites of interest. Ecologists normally use habitat availability under low flow conditions as their benchmark, as this reflects what is probably the most limiting condition in terms of flow. Low flows vary seasonally, but have a relatively high consistency from year to year.

The maintenance of substratum characteristics is relevant mainly to gravel bed and sand bed rivers as opposed to bedrock rivers, and is important at two levels. Fine materials are flushed from the surface matrix of gravel bed rivers on a seasonal basis, whilst overturning and transport of the coarse matrix occur less frequently. The first process enhances suitability of the riverbed for fish spawning, and helps to maintain an open matrix that provides refuge for invertebrates during inclement conditions such as floods. The second process cleanses coarse material of fine debris and algae, and maintains channel structure. It is therefore important that the EFA includes consideration of components of the flow regime that are able to perform these functions. ‘Flushing’ flows are small floods of relatively high frequency, that may occur two or three times a year. ‘Overturning’ flows are of a higher magnitude and occur less frequently, perhaps once every one to five years. Site-related criteria needed when ascertaining such critical flows include the particle size distribution of the bed material, the discharges needed to move different-sized particles, channel gradients, and cross-section hydraulic geometry. Also important is the rate of sediment supply from upstream, which depends on both upstream channel storage and catchment inputs via tributaries.

Assessment of the effective discharge for transport of different-sized sediments is plagued with uncertainties, due to the lack of realistic bedload transport formulae. The prediction of critical flows for entrainment in mixed bed gravel or cobble streams is especially difficult (Bathurst 1987; Komar 1996), as the movement of small particles is inhibited by larger ones. Transport can be modelled as a two-phase process (Bathurst 1987). The first phase considers the winnowing of fine particles from the coarser matrix, and the second phase considers the mobilisation of the entire bed once the larger particles start to move. In the context of the BBM, freshes, or smaller high flow events, are clearly flows which relate to the first phase of sediment transport, whilst major floods relate to the second phase.

Two alternative ways of estimating critical velocities for entrainment are presented here. Figure 14.1 gives Hjulström’s curve (Hjulström 1935), which illustrates the critical velocities required for movement of different-sized particles. Figure 14.2 gives relationships between particle diameter and critical velocity for movement, based on three different empirical equations, for the four river zones most likely to be encountered in EFAs. These relationships can be used to give a first estimate of the critical velocity required to move material of a given particle diameter. The range of values of critical velocity varies quite widely, however. When assessing these values, it should be borne in mind that many sediment transport relationships were derived using flume beds composed of uniform particles, and not using rivers. Additionally, sediment transport functions may have to be modified to take account of armouring, development of bed structures and packing. In summary, the critical velocity for entrainment is difficult to predict but, by using the different available methods plus expert judgement, one can get a feel for the limits within which one is working.

The last group of criteria identified in Table 14.1 concerns the maintenance of channel form, and thus deals with the ultimate determinant of the instream flow environment. Recommendations regarding channel forming flows may be the most problematic to provide. For instance, it is widely believed that floods of moderate magnitude, occurring once every one to two years in humid areas and less frequently in semi-arid areas, are the most important in maintaining channel form. This reflects the concept of dominant discharge, which was first postulated in the U.S.A. by Wolman & Miller (1960) and later developed by a number of researchers worldwide (Harvey 1969; Pickup & Warner 1976; Williams 1978; Andrews 1980; Williams & Wolman 1984; Carling 1988; Kochel 1988).

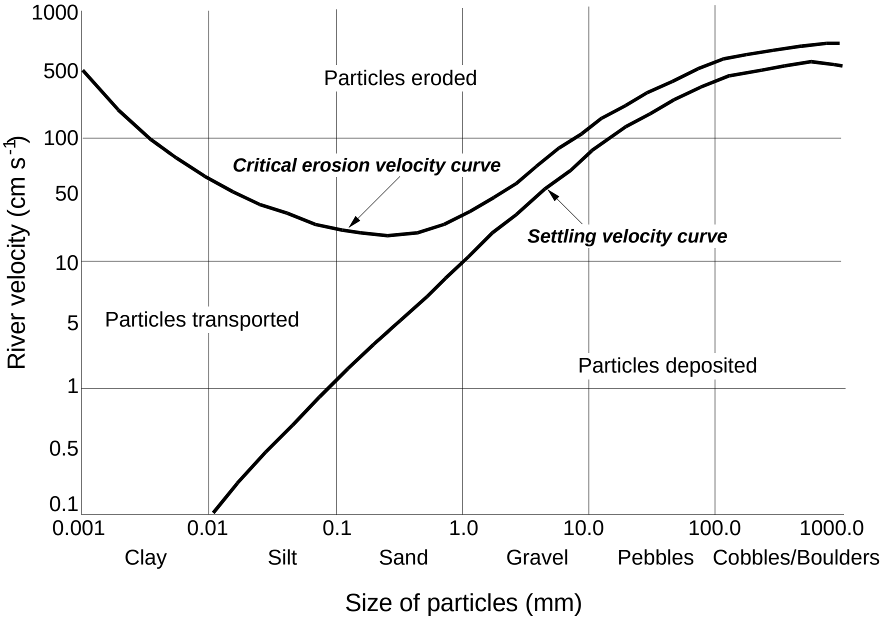


Figure 14.1 The relationship between particle size and particle movement according to Hjulström (1935). River velocity represents the mean velocity of the water column (the critical velocity). Size of particles = particle diameter.

Early work by Wolman & Miller (1960) pointed to a correlation between bankfull discharge, or the flow which effected most of the long-term sediment transport, and the flow with a recurrence interval of 1.5 years. Later research revealed that these simple relationships do not always hold. Firstly, as the flow regime becomes more variable, as in semi-arid areas, the bankfull discharge is of a higher magnitude than the 1.5 year flood and may have a recurrence interval of between three and ten years (Pickup & Warner 1976). Secondly, in channels dominated by coarse gravel or cobble, discharges greater than bankfull may be needed before the flow can cause effective bedload transport (Carling 1988). Thirdly, some channels have a complex form, with an active channel that is equivalent to the normal bankfull level and a macro-channel that accommodates extreme flood events (Graf 1988; Van Niekerk *et al.,* 1995; Rowntree & Wadeson 1999). This is the case for many South African rivers, where the macro-channel, often entrenched into a terrace, appears to take the place of a true floodplain. In terms of BBM recommendations, it is the smaller active channel that should be the focus of attention, because this is the section of the channel the form of which is determined by regular flooding. Finally, these relationships will hold only for alluvial channels. Different relationships need to be developed for bedrock channels, because they do not adjust their form in relation to discharge in the same way as alluvial channels.

Channels are dynamic features and their morphologies reflect their past sediment and flow regimes. The present imprint of any single event will depend on its magnitude, the stability of the channel, and the number and size of ensuing events. Thus, when interpreting a BBM site in terms of channel forming discharge, two possibilities should be borne in mind. Firstly, the active channel may have been widened beyond its ‘normal’ state, due to a major flood in the recent past. Therefore, the channel now may be in a phase of reconstruction, with associated channel narrowing. Secondly, the channel may have been destabilised, due to a pulse of coarse bedload moving down the channel. In summary, given the highly variable nature of the fluvial environment in South Africa and the widespread occurrence of bedrock or mixed reaches, the ‘equilibrium’ channel, or channel with a form in equilibrium with the long term discharge regime, is likely to be more of a theoretical construct than a reality.

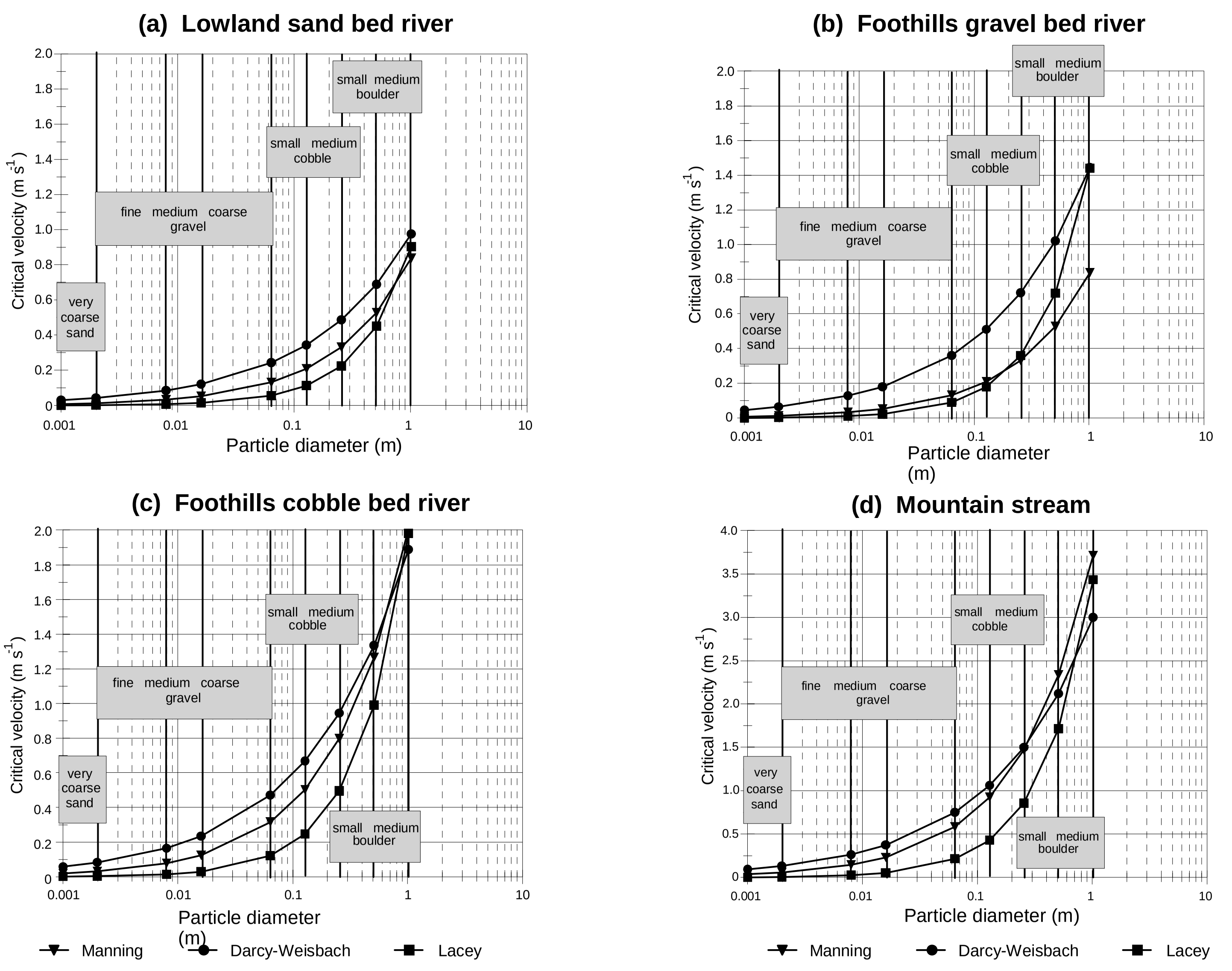
Despite these important departures, the dominant discharge concept provides a logical premise upon which to recommend channel forming flows. When applying the BBM, it has become common practice to recommend one flood discharge approximating to the bankfull level in the active channel. This is to be provided every one to two years and timed to link with flood-producing storm events of this magnitude over the catchment. It is not known, however, what the long-term effect of reducing the natural range of flood flows to one bankfull event will be. Long-term monitoring of regulated channels is thus an important requirement, in order to assess if EFRs are achieving their objectives in terms of the EMC.

14.1.2 Geomorphological impacts of impoundments

Channel form and associated physical habitat are determined by the nature of sediment in storage, and by the extent and characteristics of exposed bedrock. Any process that leads to an alteration of the nature and amount of sediment in storage will lead to a change in channel form. The geomorphological impacts of impoundments have been described by a number of authors (Kellerhals & Gill 1973; Gregory & Park 1974; Petts 1980; Williams & Wolman 1984; Erskine 1985; Sherrard & Erskine 1991). Dams have two immediate effects. By trapping sediment behind the dam wall, they reduce the sediment supply to the downstream channel. Additionally, by storing water, they reduce both the magnitude and frequency of downstream floods. The net impact of these two processes on the downstream river depends on three factors. These are the location of the reach for which the assessment is to be made relative to the impoundment, the cumulative effect of lateral inputs of sediment and runoff between the dam and the reach, and the characteristics of the reach itself.

The main potential impacts of impoundments on the geomorphological character of the downstream river are summarised below.

- Degradation and armouring immediately below the dam, due to removal of fines by sediment-free water (Hammad 1972).
- Accommodation adjustment, wherein the resistant nature of the channel and lack of potential for sediment storage inhibit significant channel change (Petts 1979). This is characteristic of bedrock channels.
- Aggradation and formation of tributary bars, due to reduced flow in the main channel being insufficient to transport continued sediment inputs from tributaries (Kellerhals & Gill 1973). This may lead to narrowing/deepening of the channel and channel contraction (Gregory & Park 1974), as the channel becomes adjusted to the reduced flood flows. This is characteristic of transport-limited alluvial or mixed channels.



(a) Lowland sand bed river

(b) Foothills gravel bed river

(c) Foothills cobble bed river

(d) Mountain stream

Figure 14.2 Critical velocity for particle movement based on three conventional formulae applied to four different river zones.

14.2 GEOMORPHOLOGICAL STUDIES IN THE BUILDING BLOCK METHODOLOGY

There are three important geomorphological issues to consider in applications of the BBM (Rowntree & Wadeson 1998): assessment of channel dynamics and potential impacts of impoundments; selection of representative BBM sites; and application of the BBM routines to each site. These activities take place at the catchment scale, river network scale and reach or site scale, respectively.

- **Catchment scale assessments**. A general assessment is made of the catchment condition and channel characteristics, to ascertain the potential for morphological change within the river.
- **River scale assessments**. An evaluation of the geomorphological characteristics of the river network is carried out, to aid the selection of BBM sites within representative reaches.
- **Reach scale or site scale assessments**.
    - At each BBM site an assessment is made, for each type of morphological unit present, of the relationship between hydraulic diversity and discharge. This assessment concentrates particularly on the relationship at low flows, because these are the flows at which suitable habitat may be critically reduced in abundance or completely lost.
    - The freshes and floods required to maintain channel form and bed condition are determined for each site.
    - An assessment is made of the likely pattern and direction of morphological change resulting from the recommended flow regime.

14.3 SEQUENCE OF ACTIVITIES

14.3.1 Identification of catchment sediment sources

The first activity, namely identification of areas within the catchment which act as major sediment sources aids assessment of the location, extent and direction of potential geomorphological change along the channel network. The potential change following flow regulation is particularly relevant. The exercise is a desktop study done by the geomorphologist prior to site selection and the site visit. The information on present and potential sediment loads and turbidity will be of interest to the water quality specialist (Chapter 15).

The methods used depend to some extent on the familiarity of the geomorphologist with the catchment, and the availability of relevant data. If the specialist is unfamiliar with the catchment, it is recommended that potential sediment source areas be derived using a GIS package such as ARC/INFO and ARC/VIEW, to generate maps of catchment variables that determine sediment production. In South Africa, these maps can be obtained from available databases such as ENPAT or WR90. Relevant variables include rainfall, runoff, gradient, geology, soils, natural vegetation, land cover or use, rural population densities and land tenure. The reader is referred to Chapter 7 of Rowntree & Wadeson (1999) for full details of how the WR90 GIS covers can be used.

Data analysis and presentation

A typical map of potential sediment sources is shown for the Thukela (Tugela) River, South Africa, in Figure 14.3 (DWAF 1995). In this example, the area of maximum assigned potential sediment yield occurs in a relatively dry area in the middle of the catchment, which is underlain by erodible Ecca shales and vegetated by karroid bush. The rural population density is high, this area having been part of the former homeland of KwaZulu. The area of lowest potential sediment yield was assigned to the upland areas, where high rainfall supports an intact cover of sour grassveld, and soil erodibility and population density are relatively low.

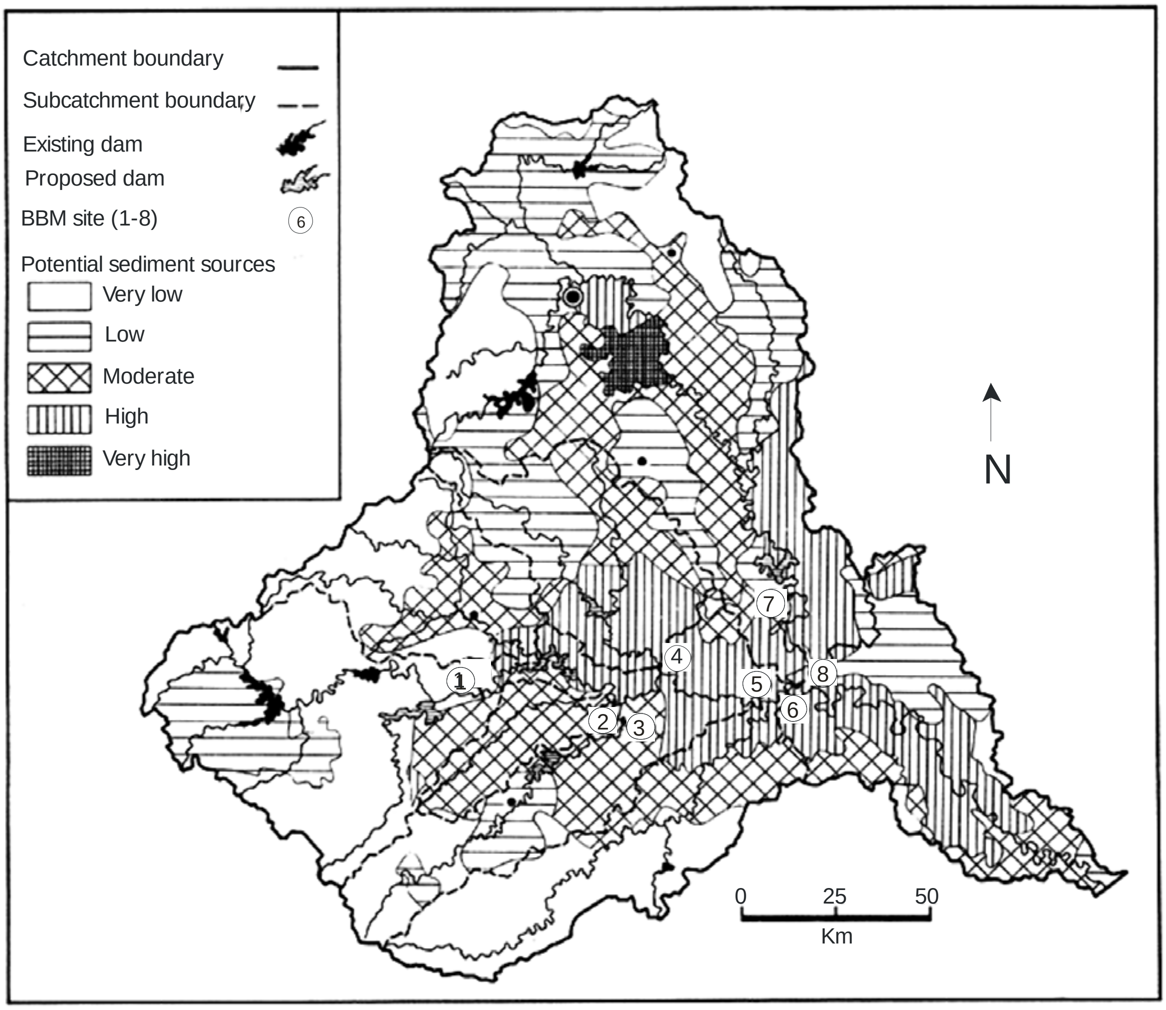


Figure 14.3 Potential sediment source areas for the Thukela Catchment (from DWAF 1995)

14.3.2 Reach analysis

Characterisation of the channel and subdivision of the long profile into morphologically uniform reaches, provides a basis for site selection and for extrapolation of results from the BBM sites to the full length of the study area. The analysis is a desktop study by the geomorphologist, done after the helicopter survey (Chapter 8). The results are used in the site selection activity and the site visit (Chapter 7).

Equipment and techniques used

Creating a long profile

Channel gradient correlates well with many other channel properties including pattern, channel type, bed material and reach type. Changes in gradient down the river's long profile should mark changes in channel characteristics and can therefore be used as a first approximation for the delineation of reaches from topographic maps. The following technique for delineating reaches down a long profile is taken from Rowntree & Wadeson (1999).

The channel gradient can be calculated from the distance between contours that intersect the channel. The standard method is to capture the blue line network data from 1:50 000 topographic maps, using the GIS pcARC/INFO. Although the use of GIS is recommended to increase efficiency of data capture and analysis, it is possible to carry out the exercise by hand, using conventional methods of map analysis.

The following paragraphs describe data capture. Note that ARC/INFO **features** are indicated in **bold** type, and *actions* or *procedures* are given in *italics*.

The course of the river is identified from the map and all contour intersections are marked. It is also useful to make a note of major tributary junctions. An example is given in Figure 14.4. The length of the river course is then digitised, marking each contour intersection with a **node**. The length of channel between two nodes is designated as an **arc**. The programme automatically *labels* each individual arc in numeric order in the direction in which it is digitised, usually from source to mouth. In the case of tributary junctions that are not coincident with contour intersections, it is necessary to adjust the arc labelling using the appropriate command in ARC/INFO. This results in the two contiguous arcs having the same number, signifying that they fall between one contour interval. This exercise produces a **cover** that contains all the relevant spatial information derived from digitising.

After *editing* and *cleaning*, the cover is *built* using the command *BUILD LINE*. This produces an **arc attribute table (.aat file**) that lists each individual arc, label ID and length in digitising units. To convert the length of arcs to metres, the cover is *transformed* into Lat-Long co-ordinates and *projected*. It is recommended that an equal-areas projection such as Albers be used. Full details of these procedures are given in the ARC/INFO manuals.

Once the cover has been projected, it can be exported to a spreadsheet program such as Quattro Pro for further analysis. In the subprogram 'Tables', the .aat file is *selected* and *dumped* as a **.prn delimited** file, which can then be imported directly into Quattro Pro. An alternative is to create a **.dbf** file. In Quattro Pro, the long profile information can be manipulated. The file contains a number of columns, of which only two are of interest here: the length of the individual arcs and their identification numbers (label_id). It is necessary to add in the contour heights of the top of each arc (upstream point) and to create a column that gives the cumulative distance from the origin. These data can then be plotted to create a longitudinal profile (Figure 14.5) and to delineate reaches.

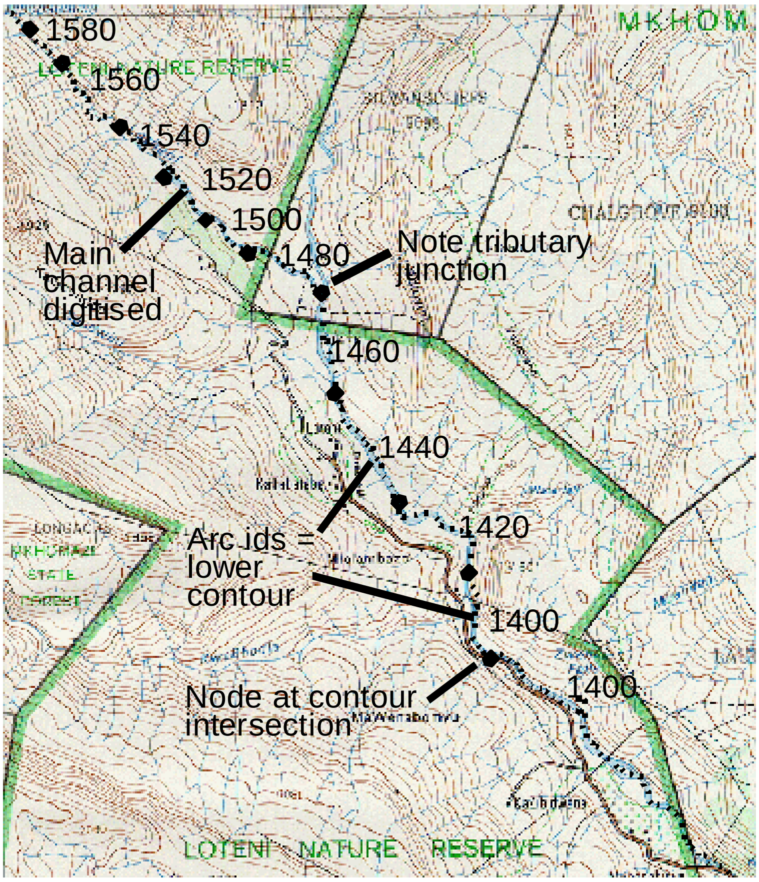


Figure 14.4 Example of a river course and contour intersections. ARC ids = lower contour: the 'id' assigned to the arc is equal to the contour height at the lower end of the arc.

Delineating reaches

It is necessary to create two more columns, that give the gradient (vertical interval/arc length), and the percentage gradient change (∇G) measured as the gradient of a given arc as a percentage of the gradient of the previous arc:

$$\nabla G = ((\text{gradient of lower arc}/\text{gradient of upper arc}) - 1) \times 100$$

A reduction in gradient is negative and an increase in gradient, positive. Reductions in gradient should always be between 0 and 100%, whereas there is no theoretical upper limit to the percentage increase in gradient. It is advisable to invert positive readings so that their ranges are reduced to 0-100%:

Inverted value = ((gradient of upper arc/gradient of lower arc) - 1) x 100

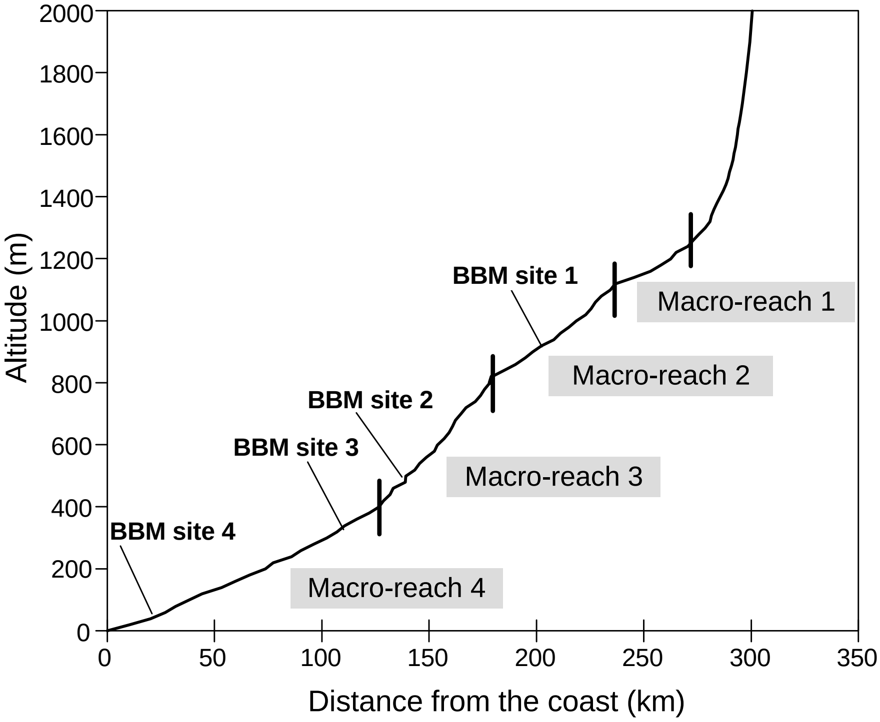


Figure 14.5 Long profile of the Mkomazi River showing macro-reaches and BBM sites (from DWAF 1998).

An important question that arises in the definition of reach breaks is: **if gradient change is important, what constitutes a significant gradient change?** It is unlikely that two adjoining lengths of river will have identical gradients, and some change in gradient is inevitable, but not every new arc represents a new reach. By listing the arc gradients and their respective changes in gradient, it is possible to visually assess the points where major channel changes are likely to take place. Generally, gradient changes of more than 50% mark distinct reach breaks, whilst changes of less than 20% are probably insignificant. Between these limits, it is a matter of subjective judgement as to where reach breaks occur.

Although the above guidelines can be used to identify significant breaks, the geomorphologist uses expert judgement to decide where and how many breaks should be identified. Often, long stretches of river with similar gradients, and therefore similar reach types, are separated by short steep sections. It may be convenient to group all these reaches into one macro-reach as was the case for the Mkomazi River (Table 14.2), but the presence of the different included reach types should be borne in mind when selecting sites. Smooth river profiles may have small but progressive changes in gradient, with channel characteristics changing gradually but noticeably down the system. In such cases, the position of reach breaks will be relatively arbitrary, unless guided by other factors such as geology and valley form.

Table 14.2 Mkomazi River: characteristics of macro-reaches (from DWAF 1998).

MACRO-REACH	GENERAL CHARACTERISTICS	GRADIENT CLASS	FREQUENCY	TOTAL LENGTH (Km)
1	0-400 m Confined to semi-confined valley; hilly topography in intrusive granites with some sedimentaries in the upper reaches; many small 1st and 2nd order tributaries; valley bushveld dominating in valleys; very high rural population density; cultivation on terraces and on fans on valley footslopes. Anabranching channels common; sandy foothill zone with mixed alluvial-bedrock channel; pool-riffle morphology; sand or gravel bars; local steepening to include pool-rapid sections.	0.0019-0.0024	4	37.71
		0.0028-0.0029	3	21.08
		0.0032-0.0036	7	42.00
		0.0041-0.0045	4	18.13
		0.0053-0.0060	2	7.07
2	400-820 m Confined to semi-confined valley; cultivation on valley floors in unconfined sections; sedimentary rocks (shales and mudstones) with extensive dolerite intrusions; forested slopes (valley bushveld); commercial farming. Single channel with well developed lateral bars; above 680 m, valley becomes steep-sided and gorge like, with an anabranching channel within an alluvial bed; rejuvenated foothills and rejuvenated cascade zones with mixed pool-riffle or pool-rapid morphologies in lower gradient sections; channels dominated by bedrock or boulder/large cobble in steeper sections; rapids, cascades and bedrock-controlled pools common.	0.0035	1	5.73
		0.0047	2	8.59
		0.0057-0.0066	4	12.94
		0.0077-0.0091	7	16.65
		0.0111-0.0143	5	7.74
		0.0216-0.1290	2	1.08
3	820-1120 m Confined to semi-confined valley within hilly topography; sedimentary rocks (shales and mudstones) with dolerite intrusions; moderate population density with extensive cultivation, especially within the Luhane catchment. Irregular channels with infrequent islands; cobble bed foothills zone with gravel/cobble bed river; pool-riffle or pool-rapid morphology; locally bedrock-controlled; narrow floodplain of sand and/or gravel may be present.	0.0035-0.0037	3	16.75
		0.0045-0.0049	3	12.75
		0.0053-0.0060	4	14.13
4	1120-1320 m Confined valley in sedimentary rocks (sandstones) with dolerite intrusions; low population density. Cobble bed foothills to mountain stream zone, with cobble and boulder bed channel characterised by plain beds, step pool morphology, rapids and pools; floodplain generally absent, but lateral depositional bench features may occur.	0.0049	1	4.12
		0.0072	1	2.77
		0.0081-0.0090	3	6.98

Refinement of reaches using mapped information relating to valley floor conditions, degree of confinement and channel pattern

Once the gradient-based reach breaks have been identified, the next step is to consult the topographic maps, geology maps and any other available data source for other evidence of channel change. The videotape of the river (Chapter 8) should be used to give supporting evidence of channel change. This is most effective if the video is filmed after the initial gradient analysis has been carried out, and the position of suggested reach breaks noted on the video footage. Table 14.3 presents a form that can be used when analysing the video. For further details of valley and channel form classification, the reader should consult Rowntree & Wadeson (1999).

Table 14.3 Video analysis form for the demarcation of reach breaks.

5 Km SECTOR NUMBER	VALLEY CONFINEMENT	CHANNEL PATTERN	DOMINANT SUBSTRATUM	REACH TYPE	BANK CONDITION
1					
2					
3					
4					
X					

Confinement:	confined (c), moderate (m), unconfined (u)
Channel Pattern:	**single thread**: sinuous (s), meandering (m), braided (b); **anabranching/divided**: sinuous (a/s), meandering (a/m), braided (a/b)
Substratum:	bedrock (b); coarse alluvium*:* boulder or cobble (c); fine alluvium*:* gravel or sand (s)
Reach Type:	**alluvial**: step-pool (Asp), plane-bed (Apb), pool-riffle (Apr), regime (Ar) **bedrock**: bedrock-fall (Bbf), cascade (Bc), planar-bedrock (Bpb) **mixed**: pool-rapid (Mpr)
Bank Condition:	stable (s), eroded (e)

Data collected

The data collected include a spreadsheet with information on altitude, distance and gradient, and data forms on channel characteristics from the map and video analysis.

Data analysis and presentation

The data are presented in the form of a long profile diagram showing reaches, together with a table summarising the main characteristics of the reaches. An example is given for the Mkomazi River (DWAF 1998). This river is characterised by a generally steep long profile (Figure 14.5) broken into many short reaches. These reaches were grouped together into four macro-reaches, which are described in Table 14.2. Once reaches have been identified from the maps or photographs, it is necessary to verify the locations of reach breaks in the field, and to describe the characteristics of reaches containing BBM sites using a prescribed inventory (Section 14.3.4).

14.3.3 Site selection

During the BBM site selection exercise (Chapter 7), the geomorphologist, with reference to the results of the reach analysis:

- advises on the representivity of selected reaches with respect to the river network;
- ensures that the channel morphology of the selected sites provides sufficient clues to guide flow recommendations.

The representivity of sites is assessed from the reach analysis (Section 14.3.2). Expert judgement may be used to answer the following questions:

- is the reach in which a site is located representative of its section of the river;
- does the site appear to be disturbed, and is there excessive erosion or deposition;
- are there clear, stable morphological features that can be used to peg channel forming flows, for example, a floodplain or, where a macro-channel is present, a lateral bench?

If the site is not considered representative of the river, but is nevertheless selected as a BBM site, a statement should be made as to how flow recommendations derived for this site should be modified to meet flow requirements for other reaches. For example, BBM site 2 on the Mkomazi River was significantly steeper, with a narrower channel, than upstream reaches (DWAF 1998). It also lacked the secondary channels identified in many river reaches. The recommended flows for this site would therefore probably be lower than those required for a wider, more complex channel.

14.3.4 Site visit for data collection

The purpose of the BBM site visits is to describe and classify the sites in terms of their geomorphological characteristics. The primary use of the data collected on site is to assist in the recommendation of flows that can maintain suitable physical habitat in terms of bed conditions and channel form. Channel changes will be the inevitable consequence of flow regulation and so the potential for, and likely direction of, such changes should also be assessed. Additionally, the general condition of the reach, and the extent to which the channel may have changed from its long-term natural condition, can be used to help assign an EMC (Chapter 11).

The optimum time for a data collection exercise is during the low flow season, when the channel is most accessible. During high flows, many features are covered by water and so observations and surveys are difficult. However, as the high flows have the greatest geomorphological effect, it is advantageous to make a second site visit during a flood event. Site visits should be made at least one month before the due date for the starter document, in order to allow time for analysis of results and report writing.

During the site visit and afterwards, the geomorphologist should work closely with:

- the vegetation specialist, as the distribution and nature of the riparian vegetation are closely linked to channel features;
- the surveyor, to ensure that significant channel features are included in the survey lines;

- the hydraulician, as the geomorphologist relies heavily on the results of the hydraulic analysis for predicting discharges necessary for initiating sediment transport and channel maintenance.

Equipment and techniques used

Survey cross-sections are laid out across the BBM site, to represent the main morphological units. For example, two cross-sections may be set out across a rapid or riffle and a pool, respectively. These cross-sections are used to give an accurate representation of the geomorphological features of interest, and to measure the characteristic flow hydraulics at the observed discharge. These latter data are the input for a hydraulic modelling exercise, which is used to estimate average water depths and velocities over the whole range of anticipated discharges (Chapter 13). For the geomorphological assessment, the cross-section(s) should be chosen to include significant morphological features, such as active channel banks and in-channel benches, which can be used as diagnostic features for advising on channel forming flows. Alluvial features should be included whenever possible, because their morphology best reflects channel forming flows and, for the same reason, pools often provide better sites than do rapids or riffles.

Standard forms for recording observations made as part of the general site assessment for geomorphology are included in this manual as Appendix 14.1. The following information should be recorded.

- A reach type should be assigned to the site, to assist later extrapolation of site results to the rest of the study area.
- Detailed field notes should be made of the morphology along the cross-sections. This information can be linked later with the survey data of the cross-sections. Evidence of past flood levels should be noted, and the position of debris lines linked to the cross-section surveys.
- A survey should be made of the particle-size distribution of the perimeter material, together with a note of the degree to which the bed is structured, and the degree of armouring and mobility of individual clasts. This information is used later in the estimation of critical discharges required for entrainment of bed material. A random selection of between 50 and 100 sample points should be taken in each significant morphological unit. The bed particles at each point should be assigned to a size class as given in Table 14.4. Particle diameter of gravels and small cobble can be measured using either callipers or a template, and a tape measure can be used for larger particles. Sand and silt size classes can be assigned subjectively, or samples can be taken back to the laboratory for sieve analysis.
- Hydraulic biotopes (Rowntree & Wadeson 1999) within each significant morphological unit should be classified according to water depth, substratum class and flow type. A systematic survey of 50 points at 1-2 m intervals along random cross-sections gives a rapid assessment of the composition of hydraulic biotopes within the site. Flow types can be classified according to Table 14.5. Surveys of the substratum and hydraulic biotopes can be carried out at the same time.
- An assessment of the advantages and disadvantages of the site with respect to its geomorphological character should be made whilst in the field (Chapter 7).

Table 14.4 Particle size classes for assessing bed and bar material.

SIZE CLASS	CLAST SIZE (mm)
Very fine sand/silt	<0.125
Fine/medium sand	0.125-0.0.5
Coarse/very coarse sand	0.5-2.0
Very fine/fine gravel	2-8
Medium gravel	8-16
Coarse/very coarse gravel	16-64
Small cobble	64-128
Large cobble	128-250
Small boulder	250-500
Medium boulder	500-1000
Large/very large boulder	1000-4000
Bedrock	-

Table 14.5 Classification of flow types (modified from Rowntree & Wadeson 1999).

FLOW CLASS	FLOW CHARACTERISTICS
Dry	Substrata out of the water.
No flow	No water movement.
Barely perceptible flow	Smooth water surface, flow only perceptible through the movement of floating objects.
Smooth flow	Perceptible flow of water, but the water surface remains smooth. A slight surface disturbance may be observed as ‘dimples’; the flow is uniform, with no significant convergence or divergence.
Rippled flow	The water surface has regular disturbances, which form low transverse ripples across the direction of flow.
Surging flow	Strongly rippled flow, with ripples forming undular waves that move downstream.
Undular standing waves	Standing waves form at the surface, but there is no broken water
Broken standing waves	Standing waves present which break at the crest (white water)
Chute	Smooth flow, generally over a short distance, with flow acceleration. Often due to flow convergence. Typically occurs in boulder or bedrock channels where flow is being funnelled between macro bed elements.
Free falling	Water falls vertically without obstruction.
Trickle flow	Very shallow moving water, that cannot be classified according to any of the above criteria.

Data collected

- Data sheets and field sketches relating to channel morphology and channel condition.
- Cross-section surveys (responsibility of the surveyor), which include points required by the geomorphologist.
- Particle-size distribution of bed material for pools, rapids/riffles and bars.
- Hydraulic biotope data by morphological unit.

Data analysis and presentation

The Mkomazi BBM site 2 is used as an example of how geomorphological data can be presented (DWAF 1998). Two cross-sections were surveyed at this site, one located on a boulder/cobble rapid and one through the upstream pool. The pool cross-section was most useful in terms of channel morphology, whilst the rapid cross-section was more useful for assessing hydraulic habitat, because of the greater variability of hydraulic habitat types.

In the upstream pool cross-section (Figure 14.6), three separate morphological channels could be distinguished. These were the low flow thalweg channel, which followed the lowest point of the river bed and normally contained water as long as the river was flowing; the active channel, which more or less coincided with the bankfull channel; and the macro-channel, which was defined by high terraces.

The particle-size distribution of the bed material is conventionally shown as a cumulative frequency curve, as in Figure 14.7. The median particle size (D_{50}), and other percentiles that were required for estimation of critical velocities for entrainment, were read from this curve.

Morphological units were described for each surveyed cross-section. Available hydraulic habitat was assessed for the observed discharge, in terms of water depths, substrata, flow types and hydraulic biotopes. Readings were taken at approximately 1-2 m intervals along cross-sections, depending on cross-section length and complexity. The proportions of flow type groups in a rapid and in a boulder riffle, based on approximately 50 random points in each place, are shown in Figure 14.8.

14.3.5 Assessment of long-term channel change

Long-term effects of an upstream impoundment on channel morphology can have implications for the EFR. If the channel morphology changes in response to changes in the flow regime so will the hydraulic rating for the site. In a desktop study following the site visit, therefore, the geomorphologist should study time series of annual floods and aerial photographs to provide the following analysis.

Data analysis and presentation

The morphological character of the channel may undergo changes due to either natural or anthropogenic disturbance, and these must be understood before future channel change can be predicted. Firstly, the observed channel morphology may represent a stage in the natural cycle of erosion and reconstruction. It is probable, for example, that many of the rivers in KwaZulu-Natal, South Africa, still bear the imprint of the floods of 1984 (cyclone Demoina) and 1987, that may have stripped out sedimentary features, such as lateral benches. These are now being reconstructed by smaller floods. Secondly, after impoundment, morphometry of the downstream channel will inevitably adjust to the changed flood frequency and sediment load.

The possible impact of previous floods can be assessed from a consideration of the past hydrological record. Care must be taken in interpreting the larger floods, which will in many cases have exceeded the gauging limits, and so their magnitude will not be known accurately. Simulated flood peaks usually have a large error factor.

Aerial photographs are a useful tool for the assessment of past changes in channel morphology. The earliest cover, available for most of South Africa, was taken in the late 1930s at a scale of 1:25 000. Thereafter, aerial photographs were taken at approximately ten-year intervals at scales ranging from 1:20 000 to 1:50 000. Channel plan features and channel morphology can only be distinguished on large-scale photographs (1:30 000 or greater), and then only for wider channels lacking overhead vegetation. The 1:50 000 cover of 1975 is of limited value, because the scale is too small to see any channel features. In South Africa, large-scale aerial photographs at 1:10 000 are available for selected rivers such as the lower Sabie. Time and financial budgets should allow for the purchase and analysis of aerial photographs, at least for the reaches in which BBM sites are located.

Assessment of potential long-term change should take into account the features of both the reaches of interest and their position in the channel network relative to the planned reservoir and sediment source areas. For example, if the main source of present day sediments is upstream of the reservoir, the downstream channels may change with impoundment from being transport limited to being supply limited. The extent of bedrock sections would be likely to increase. In contrast, if there are significant sediment inputs via tributaries downstream of the dam, the channel is likely to become transport limited due to the concomitant reduction in the frequency of flood events. In this situation, reaches would be prone to aggradation and a build up of sand and gravel bars. Such aggradation would be greatest in reaches with a moderate to low gradient. Steeper reaches would be more likely to maintain their present form.

The potential for channel change can be assessed by considering the potential sediment source area maps (Section 14.4.1) and the reach analysis (Section 14.4.2).

The presentation of results for the assessment of channel change should be in the form of a verbal report, accompanied by reproductions of sequential photographs where appropriate. Aerial photographs should be available at the BBM Workshop.

14.4 MINIMUM AND IDEAL DATA SETS

To date, the time span for the geomorphological study within a BBM application has been about 6-12 months, with only about five days set aside for a desk study and half a day per site for field visits. It has therefore not been possible to undertake any meaningful geomorphological studies of channel dynamics. Inferences have to be made from a single site visit, and from the analysis of published information such as maps.

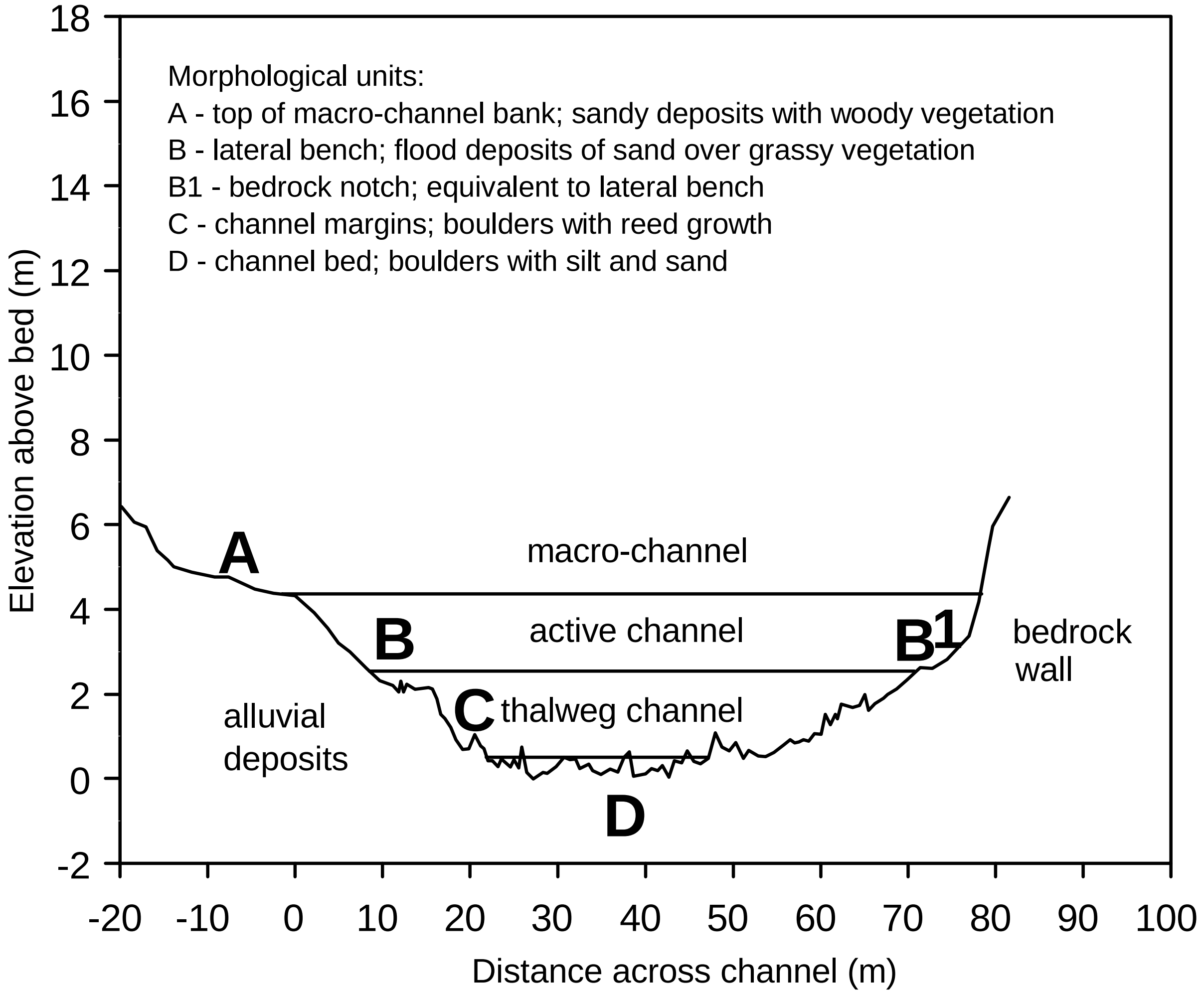


Figure 14.6 Surveyed cross-section at BBM site 2 on the Mkomazi River (from DWAF 1998). It is standard practice to illustrate the cross-section as viewed looking downstream.

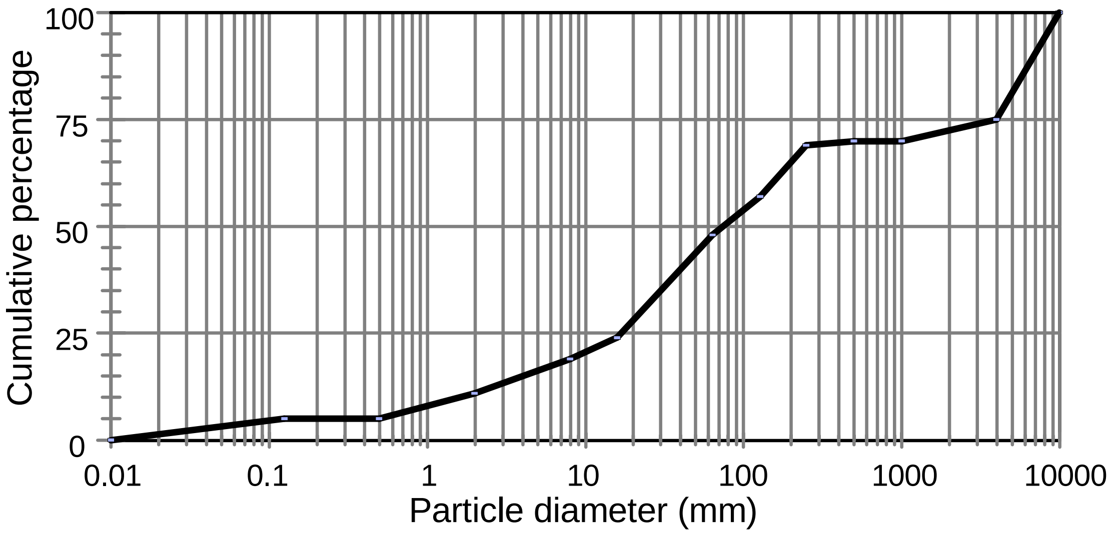


Figure 14.7 Particle size distribution for a site on the Mkomazi River (from DWAF 1998). The median diameter (D_{50}) can be read off from the graph as 70 mm.

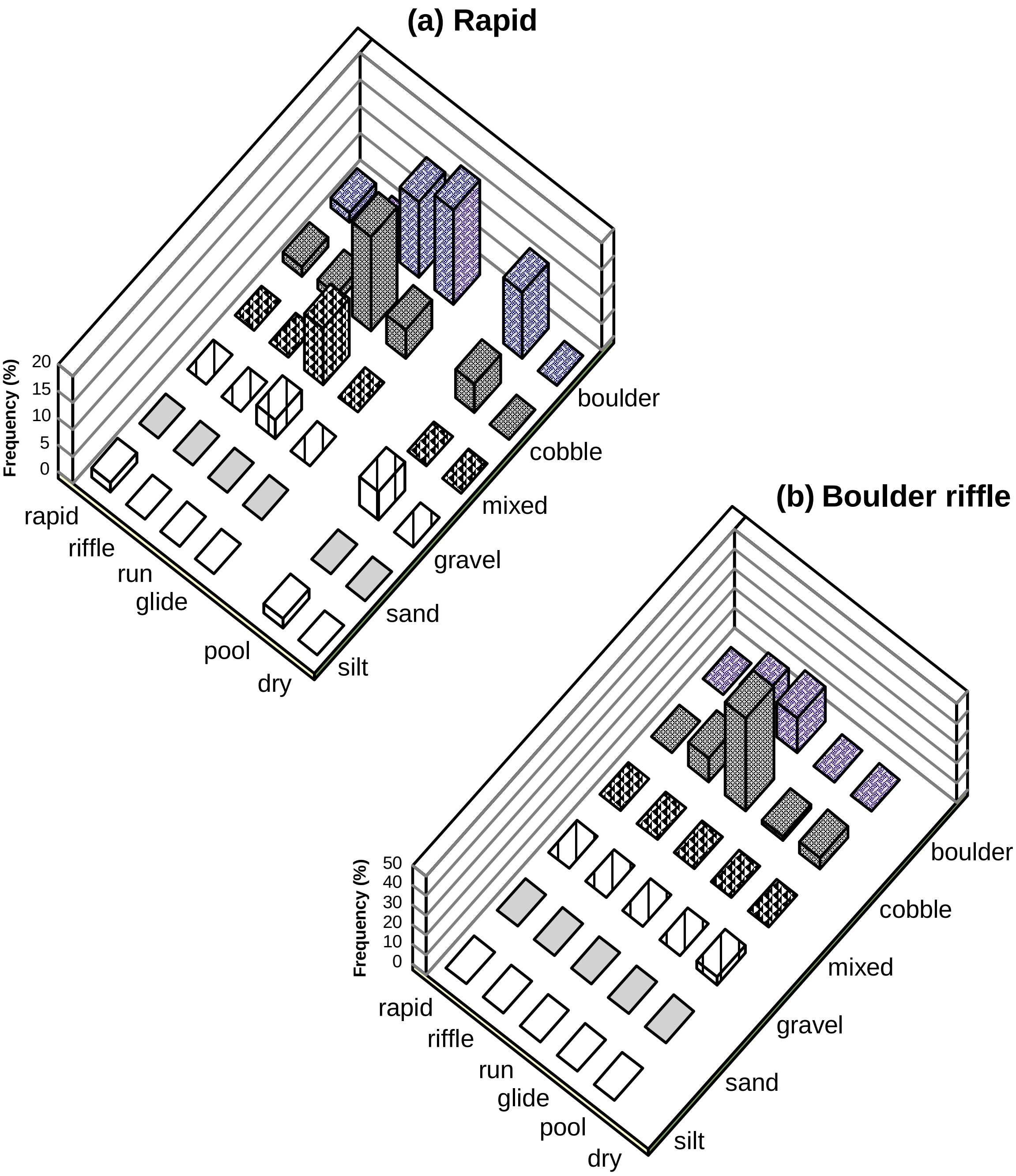


Figure 14.8 Composition of two hydraulic biotopes (a) a rapid and (b) a boulder riffle, by flow type grouping and substratum class, BBM site 2 on the Mkomazi River, at a discharge of 5.2 $m^3 s^{-1}$ (from DWAF 1998).

Flow type groupings:
***rapid:* free falling, chute, broken standing waves**
***riffle:* undular standing waves**
***run:* rippled and surging flow**
***glide:* smooth flow**
***pool:* barely perceptible flow, no flow**

Although our understanding of the morphological functioning of South African rivers has increased significantly over the last ten years, partly as a result of an increasing database created during BBM applications, there are as yet few data on the fluvial processes of sediment transport and channel change. Available information is limited in both scope and geographical extent. It is, therefore, necessary to infer process-form relationships from the international literature, which in many cases may not be directly transferable to the South African fluvial environment. An ideal data set for a river would be derived from a long-term (10-20 years) study of sediment transport and channel change. This is clearly outside the scope of a BBM application, but indicates the kind of research that is needed.

A minimum data set would be derived from the following activities.

- A desktop study to:
    - identify sediment source areas within the catchment;
    - complete a reach analysis of the river's long profile, based on map and video analysis.
- A site visit to:
    - verify the reach analysis;
    - survey and classify the channel morphology;
    - identify significant features on the channel cross-sections;
    - survey bed and bank material;
    - survey the types and distribution of hydraulic biotopes.

An extended series of field data collection activities could consist of the following components.

- Extension of field data collection:
    - an extension of field surveys within the time frame for the BBM application;
    - repeated surveys of hydraulic biotopes at different discharges;
    - refinement of medium to high flow stage-discharge relationships.
- Additional desk studies using available data:
    - studies of aerial photographs to assess channel change at each BBM site;
    - magnitude-frequency studies of relative bedload transport based on theoretical bedload equations.
- Long-term field monitoring:
    - field studies of channel dynamics and long-term channel change;
    - bedload monitoring.

14.5 STARTER DOCUMENTATION FOR THE WORKSHOP

14.5.1 Overview of the catchment

- A general description of the catchment in terms of factors affecting geomorphological response.
- Maps showing potential sediment sources and runoff zones. This information is used to assist the assessment of future channel change and to provide a general background to the BBM application.

14.5.2 River zones and reaches

- River long profile and description of reaches and macro-reaches. This information is used to assist the selection of BBM sites and to assess representativeness of these sites.

14.5.3 Sites

- Description of BBM sites, with an indication of geomorphologically significant features on the channel cross-sections:
    - distribution and abundance of hydraulic biotope at observed flows;
    - evaluation of the types of flow that are significant in terms of observed site conditions;
    - assessment of likely or possible channel changes after impoundment.

14.6 ROLES AND RESPONSIBILITIES AT THE WORKSHOP

14.6.1 Representativeness of sites

The geomorphologist provides expert input on site conditions in relation to the extended channel network.

14.6.2 Low flow habitats

Low flows have minor geomorphological significance, but the geomorphologist should be able to assist with recommendations regarding the availability of habitat.

14.6.3 High flows

High flows are of major geomorphological significance. Channel or habitat maintenance is often the primary reason for recommending floods, so the geomorphologist makes a major contribution to these discussions, as indicated below.

Flood magnitude

The geomorphologist should identify morphological features that are thought to represent the maximum extent of the active channel. Recommendation of flows is often based on the assumption that at the channel forming discharge, overtopping of the identified morphological feature results in sediment deposition and construction. It is also assumed that average velocity across the main channel is sufficient to entrain and transport significant amounts of sediment. Normally, the channel forming discharge is taken to be the mean daily discharge with a depth that just overtops the feature in question. In reality, the peak discharge during that day will probably be considerably higher, and there will be significant overtopping and deposition. The average cross-channel velocity for this discharge can be estimated by the hydraulician (Chapter 13). This velocity can be compared to the estimated minimum velocities required to entrain the median bed material (Figures 14.1 & 14.2). Although limited confidence can be placed in estimates of critical sediment transport velocities, this information can be used to corroborate the estimates of channel forming discharge, based on channel morphology.

This is illustrated using the study of the Mkomazi River (DWAF 1998). BBM site 2 is in a steep river reach in a gorge. It is in the mountain stream zone, equivalent to rejuvenated cascades. A discharge of 350 $m^3 s^{-1}$ was recommended for the maintenance flood for the main channel. The hydraulic analysis indicated that this was equivalent to a depth of 2.65 m, a wetted width of 60 m and a velocity greater than 2 $m s^{-1}$. This depth will inundate a grassy flood bench and allow sediment to be deposited on degraded areas of the bench. It should be noted that although the height of the flood bench at the point of the cross-section was only 2.2 m (Figure 14.6), the flood bench increased in height upstream. A height of 2.65 m correlated with a clear nick in the bedrock wall forming the opposite bank. A mean velocity of over 2 $m s^{-1}$ should be sufficient to move the small to medium cobble found in this section, and all but the largest boulders would be mobile.

Smaller floods may also be recommended in BBM applications. The primary geomorphological reason for requesting these is to ensure that the finer sediments are winnowed out and an open structure is maintained in coarse gravel and cobble beds. These floods will also assist in the reconstruction of degraded morphological features. There are no well-defined rules for determining the required flood magnitudes, but the velocity should be sufficient to entrain silt, sand and, possibly, fine gravel. It may be possible to link the height reached by small floods to in-channel bars or other morphological features.

The estimation of effective discharges for sediment transport and channel maintenance is the subject of a WRC project due to be completed in 2000. The method developed by Dollar *et al.* (1999) has been applied successfully at recent BBM Workshops, and once refined is expected to become a standard procedure.

Flood frequency

The recommended frequency for bankfull discharge to maintain the active channel is normally between one and three years, depending on the hydrological variability of the system (Section 14.1). The magnitude of the flood linked to any other return period can be gleaned from the hydrological record. Flood frequencies recommended by the geomorphologist should also corroborate those recommended for maintaining riparian vegetation, since morphological features provide habitat for this vegetation. It is logical to assume that frequency of discharges for the formation of channel features is related to the frequency of inundation required by different zones of riparian vegetation. The frequency of intermediate flood events will be system dependent, and will be linked to the requirements for other components. Usually, two or three such events will be recommended for a ‘normal’ season.

Hydrograph shape

Insufficient field evidence is available to support authoritative statements as to the relationship between hydrograph shape and bedload transport. The bulk of the suspended sediment load (wash load) is transported during the rising stages of the flood, but bedload transport can occur throughout a flood event. Net deposition takes place during the recession stage.

The normal recommendation is that the natural hydrograph shape be maintained as far as possible. A too-steep recession limb is likely to result in ‘dumping’ of the sediments being transported by the flood wave. A more gradual recession is probably associated with the formation of better-sorted bed forms, which provide a greater heterogeneity of habitat.

Flood timing

The required main flood event is normally assigned to the month in which the natural maximum annual flood most often occurs. The channel forming flood could, however, be released in any month of the wet season, being linked to trigger climatic events in the catchments.

14.7 ROLES AND RESPONSIBILITIES AFTER THE WORKSHOP

- Check the draft report of the workshop.
- Attend the Scenario Meetings. The application of a sediment transport model to investigate the effect of reduced flood events on bulk sediment transport would be useful, but has not yet been part of a BBM application.
- Advise on a geomorphological protocol for the monitoring programme.

14.8 EXAMPLE OF TERMS OF REFERENCE

- Attend the Planning Meeting, Site Selection Meeting and an agreed on number of site visits to collect data as per Section 14.3.
- Analyse field data, interpret aerial photographs and write a report for the BBM Workshop. Assist with hydraulic calibrations if required.
- Attend the workshop and provide specialist input.
- For the Scenario Meetings, assess any available sediment transport data to assess likely channel changes resulting from reduced flows.
- Attend and make expert input into the Scenario Meetings and Monitoring Planning Meeting.

14.9 MINIMUM AND OPTIMUM SPECIALIST TRAINING

Either of the following qualifications would be suitable:

- Masters degree in geomorphology plus relevant field experience;
- relevant B.Sc. (Hons) degree with extensive field experience.

14.10 POTENTIAL PITFALLS

There are a number of problems when recommending flows for maintaining geomorphological features of rivers. Firstly, there is the difficulty in defining ‘bankfull’ in a compound channel and relating this to a flood magnitude and return period. Secondly, there is the problem of modelling bedload transport in complex, mixed beds. Sediment transport takes place as a ‘pulsed continuum’ along the whole channel network, so the volume of inputs from upstream has to be taken into account. This is difficult in the absence of sophisticated flow-routing and sediment-routing procedures.

Additionally, too little is known about what happens to the morphometry of the channel if floods are reduced to one annual event. This is often all that is recommended within the BBM for channel maintenance, with additional reliance on larger floods still passing through the system. It is highly likely that channel change will occur under such a regime and ideally, this should be taken into account when interpreting hydraulic data in the context of channel forming discharges. The degree of channel change is, however, difficult to predict.

14.11 FURTHER DEVELOPMENTS

Research on the magnitude and frequency of channel forming discharge by E. Dollar, Rhodes University, is ongoing, through a project funded by the WRC. Further research is needed into sediment transport and channel forming discharges. Progress is being made through Dollar's project and through WRC-funded projects being carried out through the Centre for Water in the Environment at the University of the Witwatersrand, Johannesburg. The results of these research projects should contribute greatly towards the development of better methods for recommending flood flows.

The hydraulic biotope approach for assessing flow-related changes to hydraulic habitat is not well developed yet. There is significant potential in this approach for developing an effective method of quantifying how the composition and diversity of hydraulic habitats change with discharge. Results from this would compliment the modelled hydraulic data. At present, the modelled data only provide estimates of average conditions along the survey cross-sections, but the hydraulic habitat approach would provide insights into the mosaic of flow types present at a site. Observed relationships between hydraulic biotopes and morphological units could also enable extrapolation of results from the BBM sites to the intervening reaches (Rowntree & Wadeson 1996). Research into the development of this kind of approach is ongoing (this author & R. Wadeson, IWRE, pers. comm.; J. King, D. Schael & R. Tharme, FRU, UCT, pers. comm.).

14.12 MONITORING

Monitoring is carried out to assess whether or not the recommended flows are achieving their objectives. The monitoring protocol should be designed to answer four basic questions relating to geomorphology. These are listed in Table 14.6, together with recommended monitoring methods and frequencies.

14.13 CONCLUSIONS

Geomorphological assessment plays an important role in the BBM at a number of stages. Prior to the workshop, the geomorphologist aids in site selection and undertakes a catchment audit for assessing past and future channel change. The geomorphologist assesses the BBM sites, in order to develop recommendations for discharges that will maintain habitat diversity (low flows) and channel morphology (high flows). The geomorphology of the channel represents the result of many interrelated processes operating over a range of time scales. In the absence of detailed site-specific studies, therefore, confidence in flow recommendations will be moderate at best. Further research is required into channel forming processes in South African rivers.

Table 14.6 Monitoring protocol for the geomorphological component of the BBM.

QUESTION	METHOD	MONITORING FREQUENCY
Do the recommended flow discharges achieve the required stage levels in relation to morphological features?	Establish rated sections with stage recorders at each monitoring site	Continuous
Do the recommended flows maintain the required habitat diversity within the different morphological units?	Hydraulic biotope assessments (Section 14.3.3)	Twice yearly to monitor wet and dry season baseflows
Are favourable bed conditions being maintained?	Site surveys of size distribution of bed particles, and of bed condition (embeddedness, clustering, siltation)	Once a year during the dry season
Are morphological changes within the limits required by the Ecological Management Class and guided by the long-term natural channel dynamics?	Site assessments of channel morphology plus aerial surveys of reaches	Once every five years in the dry season

The focus of the BBM process is the sites. Flow recommendations are site-specific. This is probably the biggest limitation of the methodology. Perhaps more than any other specialist participating in the BBM, the geomorphologist recognises that processes operate over a wide range of temporal and spatial scales (Table 14.1). An important contribution, therefore, should be to enhance awareness of this aspect amongst the other specialists. They should understand the implications of working with sites that represent only a fraction of the river network. They also should be aware that data from the sites represent a ‘snapshot’ of what is essentially a dynamic system, responding continuously to both natural and anthropogenic disturbances. It is critical that the geomorphologist retains and presents a catchment scale and long-term time scale perspective.

15. WATER QUALITY

Carolyn Palmer, Heather Malan and Jenny Day

15.1 WATER QUALITY IN RIVER FUNCTIONING AND MANAGEMENT

Two major attributes of a river that affect ecosystem structure and functioning are water quantity and water quality. Water quantity issues (flow, velocity, depth and other hydraulic parameters) are the principle foci of EFAs. However, aquatic organisms also respond to water quality, and exhibit specific tolerance ranges and preferences for different chemical constituents. Thus, efficient functioning of river ecosystems requires provision not only of a suitable hydrological regime, but also of water of a suitable quality.

Water quality is described in the South African Water Quality Guidelines (DWAF 1996a) as the physical, chemical, biological and aesthetic properties of water that determine its fitness for a variety of uses and for the protection of the health and integrity of aquatic ecosystems. Water quality variables are classified as:

- system variables;
- non-toxic constituents;

- nutrients;
- toxic constituents.

Dallas & Day (1993) give a comprehensive consideration of these groups of variables in relation to their effects on the functioning of riverine ecosystems.

Impairment of water quality, or pollution, is a major global concern in water resource management (Dobbs & Zabel 1996; Sweeting 1996). Water quality concerns and problems are exacerbated in arid regions, where dilution cannot be used easily to mitigate the effects of effluent discharge and where concentrations of problem constituents increase under conditions of low flow.

15.2 WATER QUALITY CONSIDERATIONS IN THE BUILDING BLOCK METHODOLOGY

Despite adequate flow provisions for the maintenance of ecological structure and functioning, poor water quality can reduce ecosystem integrity. This may be avoided by a consideration of water quality in applications of the BBM. This should not be achieved by increasing flow allocations, but by indicating how water quality management issues should be addressed. Two key questions should be considered.

- What impact does flow (i.e. water volume, velocity and turbulence) have on water quality?
- What impact does water quality have on the riverine biota?

The first question requires an investigation of the relationship between river flow and water quality. Once problematic water quality variables have been identified, point source controls can be considered. If the water quality problem is intractable, there may be a decision to consider dilution flows. The ecological consequences of these, in terms of an EMC, would require evaluation. Water quality criteria are defined for the various EMCs in Chapter 11.

The second question relates to the tolerance of the biota to changes in water quality. Presently, water quality aspects are not well integrated into the BBM. This is because water quality modelling techniques are required to predict concentrations of chemical constituents and values of physical variables with changing discharge. These models are not currently incorporated into the methodology (but see Section 15.5). In addition, water quality is complex since it comprises a wide range of variables, many of which interact with one other. The responses of the biota can be affected by synergistic and antagonistic effects, the rate of change in concentration or magnitude of a given water quality variable, and acclimation. Thus, assessing the implications of proposed changes in water quality for the biota is not straightforward. At present in the BBM, most predictions of possible future water quality, and the consequent implications for aquatic organisms, are purely qualitative. Toxicological studies can, however, assist in quantifying these implications (Palmer & Scherman 1999).

15.3 MINIMUM AND IDEAL DATA SETS

15.3.1 Water quality variables

The data required for a BBM Workshop are:

- the physical and chemical water quality conditions associated with the current flow regime;
- how these conditions change seasonally and yearly;
- where appropriate, similar data for the system in the non-impacted state.

The suites of variables for which data are required, are listed below. Data on those variables shown in bold are essential. Data on the other variables will provide useful additional information.

- System variables: **pH**; **water temperature**; dissolved oxygen (DO).
- Non-toxic constituents: **electrical conductivity** (EC) or **total dissolved solids** (TDS); TSS; base cations (sodium, potassium, calcium, magnesium); other constituents such as sulphate, silica and total alkalinity (TAL).
- Nutrients: **total phosphorus** (TP); **soluble reactive phosphate** (SRP); **total nitrogen** (TN); **nitrate**; **ammonia (proportion of ionised to unionised)**; nitrite; total organic carbon (TOC).
- Toxic constituents: **metal pollutants**; pesticides; any other toxins likely to occur in the system.

Alternate classification systems for water quality parameters exist. For example, ammonia is often included under “toxic constituents” rather than under “nutrients,” and TDS and TSS may be classed as system variables.

15.3.2 Sources of data and information

Water quality and associated biological data can be obtained from the following sources.

Department of Water Affairs and Forestry monitoring data

The South African DWAF has a nation wide water quality database for rivers, the HIS database. This includes data for many variables, in addition to measurements of weir height, from which the links between water quality and discharge can be ascertained. Access can be obtained through the Hydrology Directorate, DWAF, Pretoria. The data are also presented graphically and as statistical summaries on the web site of the Institute for Water Quality Studies (IWQS, DWAF) (Appendix 15.1).

The data in the HIS database are limited, however, and measurements of DO, temperature, TSS and toxic substances are generally lacking. Depending on how recently the database was updated, the most recent values may not be available. Additionally, water samples for chemical analysis are usually taken only when the river is flowing. Thus the impacts of periods of flow cessation, or of times when the flow regime changes from perennial to seasonal, are usually not recorded. This is an important limitation, since these are the times when water quality changes may be most severe (Pollard *et al*., 1996).

Biological monitoring data

Biological monitoring data, such as those obtained using SASS4 for riverine macroinvertebrates (Chutter 1994, 1998; Dallas 1997), provide a useful indication of water quality and thus of environmental integrity. A SASS4 evaluation therefore forms part of the BBM protocol for water quality. It is important that the water quality and aquatic invertebrate (Chapter 17) specialists liaise during the EFA, in order to plan a joint sampling programme. The SASS Method and other biomonitoring methods are reviewed in Uys *et al.* (1996).

Biomonitoring and water quality sampling provide different kinds of information. Water quality data provide a ‘snapshot’ of the conditions in a river at the time of collection of the water sample. Biomonitoring data, through species composition of the aquatic communities, reflect ecologically relevant, integrated responses to water quality over some preceding time interval. The two approaches are complementary. For example, sampling the macroinvertebrates upstream and downstream of a point source of pollution may indicate that the water quality of the effluent is impacting the riverine ecosystem. It is only by using chemical analysis, however, that it is possible to pinpoint the substances responsible for the impact. On the other hand, a short pulse of polluted water might be released downstream, but because of the intermittent nature of the collection of water samples, might not be sampled and thus would not be reflected in the data set. If the impact of that pulse was sufficiently severe, however, biomonitoring could reveal the event, for example as reduced SASS4 scores.

Environmental water quality guidelines

The South African guidelines for the protection of aquatic ecosystems (DWAF 1996a) list recommended target ranges (i.e. TWQRs), AEVs and CEVs for specific water quality variables. These can be used to assess the present condition of the system and the extent of its degradation.

In order to build up a more comprehensive picture of the catchment under consideration, literature on other water quality studies carried out in that area should also be reviewed.

15.3.3 Minimum data set

The minimum data set should comprise at least seasonal (i.e. three-monthly) water chemistry and biomonitoring (SASS4) data over a complete annual cycle. The following chemical constituents should be measured: pH, conductivity (or TDS), SRP, TN, nitrate, ammonia and toxic constituents expected to occur in the system. If no chemical or biomonitoring data exist or can be generated in time, alternative strategies are available. An extrapolation can be made from an adjacent and comparable river reach for which chemical data are available. Alternatively, data can be derived from a reference site. If necessary, a data collection exercise might have to be undertaken for an entire annual cycle before the BBM Workshop. At least some indication of seasonal variability is required. If possible, high discharge events (e.g. storm runoff) should be sampled in order to give an indication of maximum loads of TSS and other constituents. Water quality variables should be analysed according to the methods outlined in DWAF (1992).

In arid areas in particular, every effort should also be made to estimate interannual variability in water quality, especially for critical variables such as SRP and conductivity.

Sampling using the SASS4 Method should be undertaken when water samples are collected for chemical analyses, as this enhances knowledge of the links between invertebrate communities and water quality, and informs on river health (PES; Chapter 4). The method of Chutter (1998) is suitable, and requires a standardised approach in terms of nets, sorting of samples, and data records. Personnel undertaking the sampling should be able to recognise habitat types (biotopes) relevant for aquatic macroinvertebrates (e.g. riffles, pools, and marginal vegetation), and to identify riverine macroinvertebrates to family level. If identification skills are inadequate, invertebrate samples can be collected and identification subsequently completed by trained personnel in the laboratory.

15.4 PROTOCOL FOR INCORPORATING WATER QUALITY IN THE BUILDING BLOCK METHODOLOGY

This protocol outlines the necessary steps and activities required for incorporation of water quality considerations into the BBM process.

15.4.1 Preparation for the workshop

Identification of representative river zones

Water quality varies naturally at various spatial scales. Most notable are variations between ecoregions and those variations due to differences in altitude, slope and distance from source. Altered water quality should be judged against the natural range of values, and so it is important to identify river reaches that are expected to have similar concentrations of chemical constituents and magnitudes of physical attributes. Subdividing large river systems by ecoregion is thus fundamental to the BBM process (small systems may sit within one ecoregion), and it is important to liaise with the other specialists involved in the following list of activities, in order to reach consensus with regard to boundaries of river reaches.

- Identify the broad climatic region and the ecoregion(s) in which the river is situated. It may be useful to liaise with the habitat integrity specialist (Chapter 8).
- Take note of the geomorphological reaches identified by the geomorphologist within the study area (e.g. mountain stream, foothill, lowland river (Chapter 14).
- Identify significant hydrological features that may have an effect on water quality, e.g. weirs, tributaries and impoundments (Chapters 8, 12 & 14).
- Use the above information to delineate reaches or segments that would be expected to exhibit similar water quality. Ensure the BBM sites are chosen with due regard to these water quality reaches.

Establish Reference or natural conditions

Where unimpacted conditions are not known, the current water quality condition of the river should be defined relative to some estimated historical condition. If necessary, realistic targets for water quality improvement can then be set. This Reference Condition can be described for each variable, by analysing trends in data sets of time series. Subsets of these time series, from the earliest and least-impacted period, allow derivation of monthly median values that may describe the pre-impacted or Reference Condition. These results can be presented as monthly box-and-whisker plots. However, if the records for the river reach under consideration do not go back to the pre-impacted era, the Reference Condition may have to be deduced from data from nearby sampling stations. Such stations should be in adjacent catchments with similar water chemistry, but that exhibit minimal degradation. Use can also be made of reference sites, if these have been designated for the area (DWAF 1999b).

Table 15.1 summarises the process for determining the Reference Condition for the categories of water quality variables listed in Section 15.3.1. Three categories of variables can be included:

- system variables and non-toxic constituents: pH, DO, TDS, TSS and water temperature;
- nutrients: ammonia, SRP and the N:P ratio;
- toxic chemicals: organics, inorganics and trace metals.

Table 15.1 Summary of the process for determining a Reference Condition for three categories of water quality variables. (See list of acronyms).

CATEGORY	WATER QUALITY VARIABLE	PROCESS
System variables and non-toxic constituents	TDS	Follow the 15% rule of the South African Water Quality Guidelines (DWAF 1996a), as modified by DWAF (1999a), or define in terms of risk to aquatic organisms (Palmer & Scherman 1999)
	pH DO Temperature TSS	Specify mean monthly values
Nutrients	SRP:TP ratio Unionised NH_3 N:P ratio	Define in relation to an unmodified river status (DWAF 1999a)
Toxic constituents	Toxic substances include organics, inorganics, trace metals	Define in relation to an unmodified river status, using South African Water Quality Guidelines (DWAF 1996a)

Table 15.2 provides the Reference Condition for several nutrients. A comprehensive example of how to derive Reference Conditions can be found in Palmer & Rossouw (2000).

Determination of present water quality status

If a DWAF water quality monitoring site falls within the appropriate ecological water quality reach (ecoregion), the available chemical data for the past three years can be used to prepare box-and-whisker plots of the key variables. These are then compared with the plots for Reference Condition mentioned above.

If there is no DWAF monitoring site within the appropriate ecological water quality reach, only a preliminary estimation of water quality can be made. This is done by extrapolation from a reach with data. If a quantified assessment of a particular reach is required, additional sampling would have to be carried out.

Table 15.2 Reference Conditions for nutrients (from DWAF 1999a). It is assumed that the Reference Conditions for phosphorus and nitrogen are specified by the limits for an unmodified river.

NUTRIENT DESCRIPTOR	VALUE OF REFERENCE CONDITION (EQUIVALENT TO A RIVER OF ECOLOGICAL MANAGEMENT CLASS 'A')
Ammonia, expressed as unionised NH_3 in mg-N ℓ^{-1}	<0.007
SRP:TP ratio	<10%
N:P ratio, where [SRP] is <0.01 mg ℓ^{-1}	10:1
N:P ratio, where [SRP] is <0.05 mg ℓ^{-1}	20:1

The operation of any dams on the river should also be ascertained. In particular, water quality in a river below an impoundment will be significantly affected by the point in the reservoir from which water is released. Water can be released from low in the dam wall (hypolimnetic discharges), from near the top (epilimnetic discharges) or, in the case of some modern impoundments, from several levels by means of multilevel offtake towers. As a result of thermal stratification in the reservoir, hypolimnetic water is often cool, deoxygenated and laden with nutrients and sediments. Epilimnetic water is warmer, well oxygenated and poor in nutrients (Petts 1989). The quality of the released water could seriously affect downstream ecosystem functioning for many kilometres, and these impacts should not be ignored. Information regarding the operation of any dam can be obtained from the regional DWAF office.

Future threats to water quality should be identified, by describing current sources of contaminants and likely future developments in the catchment. Red flag activities should be noted, for example, sewage works receiving industrial effluents; unstabilised chlorinated effluents; industries that discharge directly into the stream; and metal finishing industries. This necessitates site visits, and specialist, site-specific knowledge. It may be useful to ask relevant local authorities about the main contributors to pollution in the area. Information may also exist in reports on catchment or systems analyses. Potential sources of diffuse contamination can be inferred from patterns of land-use within the catchment.

In summary, the main activities for determining present water quality are:

- using the water chemistry data to prepare box-and-whisker plots, and deriving median monthly values for present water quality in each reach;
- identifying likely threats to water quality posed by current sources of contaminants and by future developments;

- listing potentially serious point sources of pollution;
- identifying major land-use areas in the catchment, and hence potential sources of diffuse pollutants.

Assessing the data

For each major water quality variable, the completeness of the data set should be evaluated. If this is adequate, seasonal trends and trends over the entire time series can be ascertained. The present condition can be compared with expected natural water quality as indicated by the Reference Condition. This will indicate whether water quality in the system is improving or declining.

Next, the relationship between each variable and flow is derived. This can be done by examining how the values for each variable change during the annual hydrological cycle. The concentration of TDS, for example, usually increases during periods of low flow, due to a concentration effect. The concentration of TSS, on the other hand, frequently increases during high flow events.

Use of South African Scoring System Version 4 scores to derive water quality information

The general level of 'health' of the river, the entry points of effluents, and the location of degraded reaches, can all be identified using the pattern of invertebrate distributions described by SASS4. Low scores in a reach that otherwise exhibits relatively unimpacted water quality may be indicative of sporadic releases of pollutants. It may be necessary to further investigate such phenomena using biotoxicity testing.

Preparation of a report detailing the above information

A report on water quality is incorporated into the starter document for the BBM Workshop. The other specialists, particularly the biologists, use it to help explain biological distribution patterns in the river.

The following is a list of topics to include in the starter document.

- A Terms of Reference.
- A brief description of the study site, including climate, geology, geomorphology and hydrology.
- A map of the river reaches under consideration, showing ecoregions; water quality reaches; geomorphological zones; BBM sites; significant hydrological features; DWAF monitoring sites; land use; sources of pollutants.
- An assessment of the reliability and completeness of all available data, indicating those data sets that were analysed in detail. Data should be summarised in box-and-whisker plots, graphically (e.g. time series analyses) or tables.
- A description of any additional monitoring data that were collected.
- For each variable, at each BBM site, an interpretation of trends relative to the Reference Condition and present conditions.
- A discussion, including reference to biomonitoring results and comparisons with the South African Water Quality Guidelines.
- A summary table of water quality conditions appropriate for each EMC, and of possible problem areas.

An example of a well-prepared report can be found in Dallas (1998).

15.4.2 Roles and responsibilities at the workshop

In the absence of water quality modelling, only qualitative predictions of the effect of changes in discharge on concentrations of chemical constituents and levels of physical variables can be made. At the BBM Workshop, cross-sections for each BBM site, prepared by the hydraulics engineer, will be presented (Chapter 13). In addition, the effect of specified reductions in flow on the hydraulic characteristics of each site will be calculated and discussed. These hydraulic characteristics include velocity of river flow, water depth and wetted perimeter. Through examination of the cross-sections and consideration of the hydraulic characteristics, limited predictions can be made with regard to the effect of changes in flow on water quality. For example, the cross-section for a site may show that at a given discharge, pools of standing water will form. If, in addition, the levels of nutrients in this reach are predicted to be high, the water quality specialist might predict an increased risk of eutrophication and algal blooms during summer. As a further example, if the flow is reduced so that water no longer flows over riffle areas, and shallow pools form, they are likely to have elevated temperatures in summer. If, due to organic pollution, biological oxygen demand (BOD) in the pools is high, there will be an increased risk of depressed DO concentrations and, possibly, of fish kills.

The water quality specialist should also consult with the geomorphologist, who will advise on the predicted changes in movement of sediments and bed material with manipulations of the flow regime. Particularly in systems with elevated nutrient levels, it may be important that, at intervals, water velocity is sufficiently high to flush out pools and stagnant areas, move cobbles, and scour fine sediments and adsorbed pollutants from the system.

Considering these predictions, the water quality specialist, together with the ecologists, should advise on flows that should maintain the required EMC, and avoid flow conditions that would degrade river condition beyond what the EMC indicates is acceptable. The specialist should also highlight potential problems in water quality, so that managers can consider alternative management options.

15.4.3 Roles and responsibilities after the workshop

A process of scenario building occurs after the meeting, in which flow regimes other than the workshop EFR are considered (Chapter 22). The consequences of each of these potential flow regimes in terms of water quality are considered, together with feasible management options. Such options may include source directed controls (DWAF 1999b), catchment management solutions, or dam operating rules for dilution. Each scenario is assessed in terms of its ability to meet the EMC for the river or river reach. Scenario building is complex and the process still requires extensive development.

15.5 FURTHER DEVELOPMENTS

15.5.1 Initiatives arising from the new Water Law

Development and implementation of the water quality component of the ecological Reserve (DWAF 1999a) will accelerate the incorporation of water quality assessment into the BBM. In particular, the water quality of stretches of rivers will be described in terms of their unimpacted condition (Reference Condition), present condition (PES) and desired state (EMC). Present water quality classes will range from A (pristine) to E/F (highly modified), and future ones from A-D (Chapter 4). Table 15.3 provides an outline of a preliminary system to classify the condition of aquatic ecosystems, incorporating a water quality component.

Table 15.3 An outline of the preliminary basis for a system to classify aquatic ecosystem condition in South Africa (from Palmer 2000).

CLASS A	***Water quality**:* Unmodified. Allow minimal risk to sensitive species. Remain within the TWQR (*sensu* DWAF 1996a) for all constituents. ***Water quantity**:* Natural variability and disturbance regime - allow minimal modification. ***Instream habitat**:* Allow minimal modification from natural conditions. Set resource quality objectives (RQOs; DWAF 1999b) with water quality, water quantity and habitat components. ***Riparian habitat**:* Allow minimal modification from natural conditions. Control land-use in the riparian zone. ***Biota**:* Allow minimal modification from Reference Condition as defined by the rapid bioassessment procedure SASS (Chutter 1994).
CLASS B	***Water quality**:* Use Aquatic Ecosystems Guideline values (DWAF 1996a), such as CEV and TWQR, to set objectives which pose slight risk to intolerant organisms. ***Water quantity**:* Use an environmental flow methodology, such as the BBM (King & Louw 1998), to set flow requirements that allow only slight risk to intolerant organisms. ***Instream habitat**:* Allow slight modification from natural conditions. Set RQOs with water quality, water quantity and habitat components. ***Riparian habitat**:* Allow slight modification from natural conditions. ***Biota**:* Allow slight modification from Reference Condition. Especially intolerant biota may be reduced in numbers or extent of distribution.
CLASS C	***Water quality**:* Use Aquatic Ecosystems Guideline values such as AEV, CEV and TWQR to set objectives that allow only moderate risk to intolerant biota. ***Water quantity**:* Set EFRs that allow only moderate risk to intolerant biota. ***Instream habitat**:* Allow moderate modification from natural conditions. Set RQOs with water quality, water quantity, and habitat components. ***Riparian habitat**:* Allow moderate modification from natural conditions. ***Biota**:* Allow moderate modification from Reference Condition. Intolerant organisms may be absent from some locations.
CLASS D	***Water quality**:* Use Aquatic Ecosystem Guideline values (AEV, CEV, TWQR) to set objectives which may result in high risk to intolerant biota. ***Water quantity**:* Set EFRs that may result in high risk of the loss of intolerant biota. ***Instream habitat**:* Allow a high degree of modification from natural conditions. Status dependent on quality, quantity and habitat objectives. ***Riparian habitat**:* Allow a high degree of modification from Reference Condition. ***Biota**:* Allow a high modification from Reference Condition. Intolerant biota unlikely to be present.

TWQR: Target Water Quality Range - the management goal for the protection of aquatic ecosystems.

CEV: Chronic Effect Value - the concentration limit which is safe for all or most populations even during continuous exposure.

AEV: Acute Effect Value - the concentration at and above which statistically significant acute (less than 96 hours) effects are expected to occur.

15.5.2 Incorporation of water quality modelling in the Building Block Methodology

A procedure is presently being developed to more comprehensively integrate water quality into the BBM (WRC project K5/956: "Development of numerical methods for assessing water quality in rivers, with particular reference to the IFR process"). This includes incorporation of the Reserve methodology (DWAF 1999a; Chapter 4), as well as the use of numerical models to make quantitative predictions of changes in water quality variables in response to changes in flow regimes. Part of the project is concerned with assessing the implications of proposed changes in water quality on aquatic biotas. An investigation will be carried out into the use of the Biobase (see below) for this purpose. Another avenue of research will be the extraction of empirical tolerance ranges for selected key invertebrate species, in conjunction with the South African Water Quality Guidelines (H. Malan, FRU, UCT, pers. comm.).

15.5.3 Biological/chemical database: the Biobase

The natural distribution of aquatic organisms is associated with geographic patterns of water quality. A biological/chemical database (called the “Biobase”) has been developed at the FRU, UCT, Cape Town. This uses all available South African data sets where biological (macroinvertebrate) and chemical data were collected simultaneously. This screening tool can be interrogated interactively to evaluate, or predict, the expected or desired macroinvertebrate assemblages associated with natural background water chemistry (Dallas *et al.,* 1998, 1999). Future phases in the development of the Biobase will include capturing additional data, and designing a mechanism whereby additional information can be added by individual researchers. The Biobase and a User Manual are being distributed on CD-ROM via the WRC (H. Dallas, FRU, UCT, pers. comm.).

15.5.4 National Biomonitoring Programme for Riverine Ecosystems

A comprehensive biomonitoring programme, using SASS4, is being developed for all the major rivers of South Africa. Known as the National Biomonitoring Programme for Riverine Ecosystems, or the River Health Programme, it is already in operation in Mpumalanga and will soon be extended to other parts of the country (IWQS 1999; Appendix 15.1). Details can be obtained from the National Biomonitoring Programme for Riverine Ecosystems, IWQS, DWAF, Private Bag X313, Pretoria, 0001.

A further project (WRC project K5/1017: “The development of a biomonitoring method using protozoans for assessment of water quality in seasonal/ephemeral rivers and groundwaters”) is currently being undertaken in the FRU, UCT (M. Joska, FRU, UCT, pers. comm.). This project is assessing the value of protozoan assemblages as indicators of water quality, as an adjunct to using SASS4 as a biomonitoring tool.

15.5.5 Empirical tolerance data

Currently, few empirical tolerance data exist for southern African organisms or for standard test organisms exposed to local conditions. Exceptions are values for macroinvertebrates subjected to a variety of inorganic salts (Goetsch & Palmer 1997; Palmer & Scherman 1999), standard test organisms exposed to whole effluents (Slabbert *et al*., 1998a, b), fish exposed to metal ions (Van Vuren *et al*., 1999) and a local invertebrate exposed to a variety of trace metals (Tian 1996; Musibono & Day 1999). Tolerance data are also given in Dallas & Day (1993). Research in this field continues, however, and two WRC-funded projects are currently under way at the IWR, Rhodes University, Grahamstown. The projects are titled “The use of indigenous riverine organisms in applied toxicology and water resource quality management” (WRC project K5/955) and “The use of *Daphnia* spp. and indigenous river invertebrates in whole effluent toxicity testing in the Vaal catchment” (WRC project K5/815).

15.5.6 Other developments

The DWAF water quality database, titled “Water quality on disk”, will shortly be available on CD-ROM (D. Hohls, Council for Scientific and Industrial Research (CSIR), Pretoria, pers. comm.). Information is available on the CSIR web site (Appendix 15.1).

15.6 CONCLUSIONS

The assessment of water quality requirements for riverine ecosystems entails a considerable degree of subjectivity. This is particularly true when, for example, dividing a river into water quality reaches. It is thus necessary to employ a specialist with considerable expertise in this field, including knowledge of biomonitoring and of the chemical processes occurring in freshwater systems.

In order for aquatic ecosystems to function adequately, it is essential that, in addition to appropriate flows, water of suitable quality is supplied. Although consideration of this factor is currently included in the BBM, it is not adequately addressed yet. Forecasts of flow-related changes in water quality are presently qualitative, and need to become quantitative. Furthermore, the process needs to be taken further, so that the responses of the aquatic biota to changes in water quality can be predicted. Current research thrusts (Section 15.5) are aimed at meeting these objectives.

16. VEGETATION

Nigel Kemper and Charlie Boucher

16.1 VEGETATION IN RIVER FUNCTIONING AND MANAGEMENT

Vegetation is a dominant part of most riverine ecosystems, where it fulfils a number of critical functions of which only a few are mentioned here. Aquatic and riparian vegetation stabilise river channels, banks and floodplains; contribute towards the attenuation of floods; influence water temperature and quality; and provide habitat, refuge and migration corridors for terrestrial and aquatic fauna. The structure, composition and overall condition of the vegetation determine the degree to which it is involved in ecosystem functioning. The vegetation also provides many resources used by man, including food (Chapter 9), and has an aesthetic component that is valued by man. Although important, these latter aspects are not dealt with in this chapter.

Plant roots bind the surface of the soil to varying extents, providing resistance to erosion by water. The superficial roots of annuals and sedges provide an initial stability to loose substrata, but have little resistance to strong flows. Their shallow roots also render them susceptible to drying out of the substratum. Shrubs and trees are deeper rooted and can utilise subsurface moisture. They tend to survive for longer periods, and their permanent cover lends longer term and greater stability to the land.

Plants, by their presence, offer resistance to the passage of water. Riverine wetlands are particularly relevant to flood attenuation as they slow the overland flow of water, allowing it more time to soak into the soil. Slow flows have a low carrying capacity for suspended materials and have low erosive effects. The slowing of current speeds by plants such as the reed, *Phragmites*, therefore limits bank erosion, and can result in bank accretion through the deposition of suspended materials.

Dense and overhanging vegetation creates shade that results in cooler water and reduced fluctuations in temperature. Temperatures that fluctuate through too great a range may preclude many species from inhabiting a river reach. Plants absorb nutrients from water and fix them in their growth products. These nutrients are released again once the plants or parts of plants decompose. Allochthonous organic material from riparian vegetation is one of the principal food sources for the riverine fauna. Removal of plants from wetlands and streams serves to remove this food source, as well as stored nutrients.

Marginal vegetation creates prime habitat, such as feeding and breeding grounds, as well as shelter, for aquatic insects and juvenile fish. Most trees and shrubs that line waterways are restricted in distribution to the riparian zone and atypical of the larger environment. They create important habitat, which is most dramatically demonstrated by desert rivers with a “linear oasis” of riparian vegetation in an otherwise arid environment. These oases provide shelter and food sources for both aquatic and terrestrial animals, as well as migration and dispersion routes through relatively hostile environments for different plant and animal species.

16.2 VEGETATION STUDIES IN THE BUILDING BLOCK METHODOLOGY

Riparian (and less commonly other) vegetation is one of the three biotic components commonly applied in the BBM for the overall assessment of EFRs, the other two being aquatic invertebrates (Chapter 17) and fish (Chapter 18). Unlike these other biotic components, which are primarily good indicators of low flow requirements, the vegetation component is a good indicator of both low flow and high flow requirements.

Depending on the characteristics of a river reach, riparian vegetation commonly occupies a range of positions relative to the river channel (Table 16.1). Marginal vegetation in the form of mesic grasses and sedges is often found on the edges of the wetted area, while other herbaceous and woody species may occupy this area as well as others further away from the river, on the macro-channel floor or macro-channel bank. This wide distribution of riparian vegetation, and its distinct delineation into vertical zones each linked to different magnitudes, durations and return periods of high and low flows, provide the basis of how vegetation is used within the BBM to recommend on future flow patterns. Each vegetation zone experiences specific patterns of inundation and exposure (Table 16.1 & Figure 16.1) (Boucher 1998;

Boucher & Tlale 1999), and requires something approximating that flow regime to continue to exist in the river system. Using this knowledge, recommendations on flows for the maintenance of vegetation can be made. These recommendations are not used in isolation, but combined with those provided by other ecological specialists, to give a consensus, holistic recommendation on environmental flows.

Due to the general paucity of information about the links between riparian plants and river flow, and the complexity of riparian zones typically associated with southern African rivers, the recommendations rely heavily on professional experience and judgement. Examples of the kinds of knowledge needed are outlined below.

Algae and diatoms are short-term indicators of water quality change, providing information about prevailing water quality over the preceding few days or weeks. Algal blooms are generally the result of nutrient enrichment or stagnation of the water. Some algae are poisonous and this can have economic consequences for stock farmers or wildlife.

Submerged macrophytes indicate that relatively quiet water of stable depth occurs for quite long periods. The water must be relatively clear and low in nutrients to support this type of vegetation.

Mosses occur on substrata that remain moist for a few months at a time. Where the water level remains at a relatively constant level for a several months, some species may become established in very shallow water on rocks or banks.

The herbaceous flora of riparian zones provides information about conditions that have prevailed over short time spans, usually one to two years in the case of annuals (e.g. exotic weeds such as *Xanthium strumarium),* or two to five years in the case of perennial herbs (e.g. *Cyperus textilis*). Annuals are the first colonisers of disturbed areas, occurring in areas of deposition, erosion or heavy utilisation. A high percentage cover of annuals indicates regular disturbance of an unstable substratum such as sand. Perennial herbs along the banks respond to intermittent, often regular, stress conditions, characteristic of areas that are periodically but regularly inundated by relatively shallow water (e.g. of about 0.25 m), then exposed again. A change from fluctuating flow levels to long periods of constant flows results in this element becoming denser, although the width of the zone may decrease as it is determined by variation in inundation levels.

Riparian shrubs (e.g. *Salix mucronata*) may be used to interpret prevailing riparian conditions over an intermediate period (5-25 years). However, both annual differences in water levels, as well as variations in regional climate from drought to wet years, also influence flowering responses of some shrubs.

Indigenous trees (e.g. *Celtis africana*) generally live for at least a century. They need specific events and conditions for their establishment. Their presence or absence and their condition (stunted or luxurious) can give an indication about dramatic events such as very wet cycles. Utilisation by man can cause havoc to this element as tree recruitment and establishment are intermittent.

Table 16.1 Model of relationships between riverine vegetation zones and flow regimes (from Boucher & Tlale 1999).

LOCATION	VEGETATION ZONE	INUNDATION INTERVAL	ABBREV.	MARKER
				Debris Line
Dry Bank	Back Dynamic Zone Transitional	Approx. >20 year Floods	BD	
	Tree/Shrub Zone	2- approx. 20 year Floods	TS	
	Lower Dynamic Zone Transitional	Within Year Floods	LD	Bottom Dry Bank Top Wet Bank
Wet Bank	Shrub Zone	Wet Season Freshes	WS	
	Sedge Zone	Wet Season Low Flow	WE	
Aquatic	Rooted Aquatic Macrophyte Zone Transitional	Dry Season Freshes	AM	Perennial Free Water
	Algae	Dry Season Low Flow Free Water throughout the year	AA	

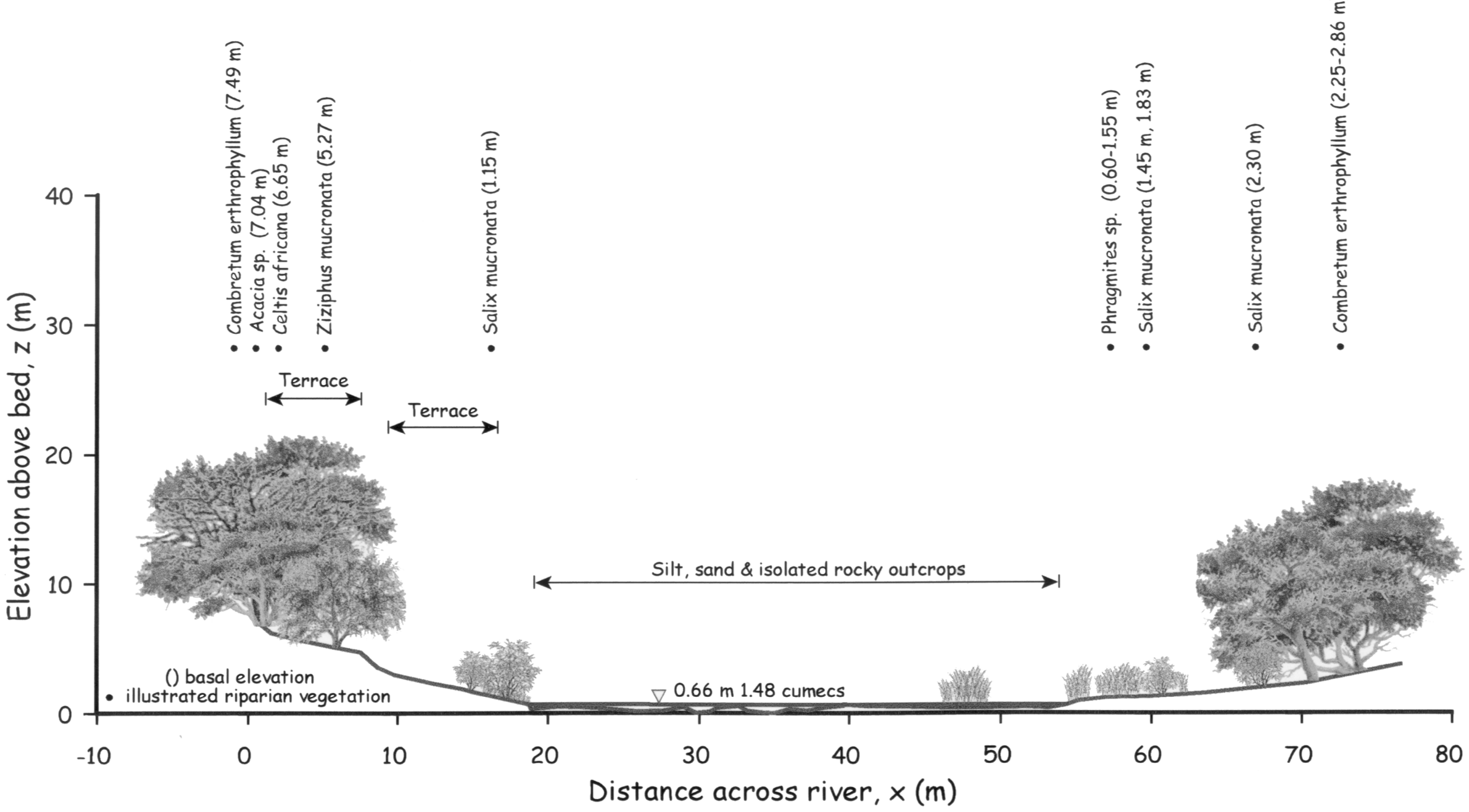


Figure 16.1 Example of a surveyed cross-section (C) showing the positions of various vegetation zones and species, for BBM site 1 on the Thukela River. Cumecs - discharge as $m^3 s^{-1}$.

16.3 SEQUENCE OF ACTIVITIES

16.3.1 Site selection

The purpose of this first activity is to identify and select BBM sites that have the characteristics that will enable each specialist to advise on flows to achieve the designated EMC. From the perspective of riparian vegetation, this requires, as far as possible, the use of sites with healthy, representative and indicative indigenous riparian vegetation. The activity preferably takes place during low flow conditions, so that as much vegetation as possible can be assessed.

Possible sites are first located on aerial photographs or after studying video footage of the river, and then visited. High resolution maps, such as recent orthophoto maps (1:10 000 scale), may be necessary to guide access to the sites. Recent aerial photographs of potential sites are an alternative to orthophotos, but require a portable stereoscope for viewing them in the field. A GPS is invaluable for pinpointing the sites and any survey lines.

Selecting a site based on vegetation criteria

The protocol for site selection is as follows:

- visit some easily accessible sites within the study area to gain a basic understanding of the nature of the vegetation along the study river;
- study the aerial video of the study area (Chapter 8) to determine the best sites with natural vegetation cover; identify more sites than are required for botanical purposes, as the selection process is multidisciplinary and some suitable ‘botanical’ sites may be rejected because they are not acceptable to other disciplines;
- visit the sites as part of the BBM team, and assess each potential site before making a final selection of sites.

The present vegetation state of a BBM site is assessed in terms of its species composition, size/age structure, recruitment rate, and distribution and zonation relative to the river and the macro-channel floor and bank. Thereafter, the riparian vegetation dynamics which have evidently taken place over time are considered in terms of their links to prevailing physical and hydrological conditions as well as to non-flow related disturbances that have occurred at the site. Riparian zones are often highly disturbed and, as such, may be totally or partially devoid of riparian vegetation, particularly woody vegetation. The overall picture of site dynamics needs to be developed, and then used to ascertain the extent to which hydrological characteristics and history are responsible for the present state of the vegetation.

Other features are also considered during site selection. For instance, the vegetation should be representative of the river reach of interest. A site located within an alluvial reach, for example, should have vegetation that displays alluvial characteristics, including riparian species typical of the region. It is of little value identifying a BBM site in an inaccessible area simply because it has a healthy riparian community, if the characteristics of the vegetation there are more indicative of a part of the river system not included in the study.

It is also essential that the vegetation present has some form of indicative value (i.e. indicator types or species). Such vegetation would comprise species with known or partially known water requirements, or whose distribution patterns, age structure or recruitment rates are determined by specific flow-related characteristics of the river at the site.

With such considerations in mind, a decision to accept a site from a vegetation perspective is finally made. This decision is usually quite a clear one as long as present vegetation conditions are largely explained by hydrological characteristics at the site. Sites where non-flow related disturbances are the primary determinants of the state of the vegetation have very little value for assessing flow requirements. The disturbances that are usually responsible for this situation are those of large-scale vegetation removal for farming, fuels or building purposes or the impacts of intensive grazing and browsing by livestock.

Ideal sites display the following characteristics:

- a wide diversity of different indigenous riparian species which are representative of the specific reach, with a sufficiently large population of the dominant or characteristic species;
- a range of age classes from seedlings through to mature individuals for most species present, but particularly of the dominant and selected key species;
- a range of vegetation zones linked to different flow and other environmental gradients;
- well-established connectivity between the river and the riparian zone;
- clear vertical definition of vegetation zones, indicating a sensitive response to flow-related conditions;
- easy access to both banks.

Where such vegetation is incomplete or absent, experience of the riparian vegetation and flora of a region can assist in the reconstruction of critical features, such as the relationship between the floral species present and flow levels. However, this introduces an element of uncertainty to associated flow recommendations. Even sites that possess excellent vegetation attributes may not necessarily survive the final selection process, as site selection is a multidisciplinary procedure. It may well be necessary to make a tradeoff between the ideals of one component and those of another in order to achieve the best overall site. For example, the site selection group may settle for a site with less than ideal vegetation characteristics, but which is conducive to high quality hydraulic modelling (Chapter 13).

16.3.2 Site description

The principal way in which selected BBM sites are described is through channel cross-sections. Botanical cross-sections are termed “transects”, reflecting that they have width as well as length. At each site, at least one, but preferably three or more transects are established to determine and describe the relationship and distribution between substrata and vegetation. Selection of a vegetation transect is done by optimising the number of important plant species and clear vegetation zones through which it would run (e.g. Figure 16.1). A variable transect width may be used to accommodate different kinds of vegetation, with those parts describing the tree zones, for instance, being wider than the parts covering herbs and mosses. In some instances, it might be necessary to examine a transect through an area chosen by another discipline so that detailed characteristics of particular vegetation can be described for the purposes of the other discipline (e.g. as a place where fish might spawn).

Other specialists also choose suitable cross-sections or transects but ultimately, as with site selection, only a limited number can be selected to describe the site. This may require compromise, and the decision should be reached with consensus of the full BBM team.

Chosen cross-sections are surveyed (Chapter 13), with important features such as indicator plant species and the beginning and end of vegetation zones included (Figure 16.1). Important plants to locate on the survey lines are ones with reasonably well understood flow requirements, or that are located in areas possessing specific flow requirements. For example, a patch of *Typha capensis* in a small side channel, a *Ficus* seedling within a reed bed, or a mature individual of the dominant woody species on the macro-channel floor, all qualify as potentially important plants. All important plants and zones are identified during the initial site investigation and marked with brightly coloured, plastic nursery tags (or iron pegs, paint or similar). The tags are then numbered in sequential numerical order, using a permanent black marker pen, from the top of the macro-channel bank towards the edge of the water. The numbering continues from the water's edge on the opposite bank to the top of the opposite macro-channel bank. These tagged points are later located on the cross-sections as these are surveyed (Chapter 13), by capturing the position of the base of the marked plant or of the precise boundary between the different vegetation zones.

16.3.3 Data collection

For each transect and vegetation zone, within the riparian zone, a list of the species content, the cover abundance of each and the structure (life forms and height classes of species) are recorded. The sample size in each vegetation zone is variable depending on the breadth of the zone and the length that can be assessed visually, which is usually in the order of ten metres. The basic dictate is that the contribution to cover by each element is assessed on a percentage basis. Small mosses cannot be assessed over a wide area because they cannot be identified at distances. Trees are visible from afar so they can be assessed over a wider area. Thus, tall plants or large individual clumps of smaller plants, which are not within the transect boundaries but are nearby, are simply 'pulled onto' the transect during the survey. The width of the transect in each vegetation zone is recorded, and the area occupied by each species within each zone estimated per bank. Some consistency of sample size within each zone is preferable, but not essential.

When time is limited, records are completed for a selection of species that are known to be characteristic (in the phytosociological sense), significant (locally prominent) or important (botanically or economically). These species offer most information, but their selection could preclude attention being paid to locally important species.

For each transect, records are also completed of the general slope, aspect, altitude and adjacent valley features, and of the adjacent vegetation on each bank. Precise information on all relevant environmental features in each vegetation zone is recorded, including data on the slope, horizontal distances and vertical heights above water level of the upper and lower boundaries of each zone. The surveyor should be able to provide many of these data from the cross-section surveys (Chapter 13). Substratum types along the transects are noted, and a superficial soil sample is taken from each zone. Any signs of erosion, deposition or other disturbances within the different zones are noted, particularly where animal or human activities might be exerting an influence on the vegetation. Signs of historic channel changes are recorded, together with their possible effects on the vegetation.

Such site data are collected as many times as possible within the budgetary and time constraints of the study, preferably at different flow levels during different seasons. This contributes to an understanding of the determining factors responsible for the spatial and temporal distribution of species, and their various size classes. It is of considerable value to collect the data at the seasonal extremes of low flow, during winter and summer, and if possible during elevated flow events.

Tables 16.2, 16.3a & 16.3b provide examples of data sheets that can be used during the collection of vegetation data. They provide the following kinds of general information (see also above):

- name of the river;
- BBM site number;
- site coordinates;
- date of visit;
- cross-section number;
- a sketched plan of the site or a cross-sectional profile;
- other relevant site notes.

Botanical information collected along the transect, which will be linked to the individual surveyed cross-section, and recorded on the various data sheets includes (see also above):

- the starting point for plant numbering, such as top of left-hand bank (LHB) or right-hand bank (RHB);
- the species of plant or name/description of the vegetation zone;
- the number of the plant or vegetation zone (zones are marked at each vertical boundary);
- the positions of the various plant species and zone boundaries, to aid with the survey or later BBM activities. The surveyors use a copy of the data sheet shown in Table 16.3a to ensure that all points of interest are surveyed. This is particularly important where the vegetation is dense and the tags are hard to find;
- the size class and phenological state of the plant (herbaceous, seedling, or approximate height in metres).

Data collected using the forms shown in Tables 16.3a & b are also suitable for comparison using both phytosociological classification and ordination techniques.

Other data collected at each BBM site are concerned with the site and vegetation characteristics relating to the flow level at the time of the visit, and to the responses of the vegetation to previous flow levels. These data are used extensively during the BBM Workshop, and form the empirical basis of many of the flow recommendations. This type of information is gathered during every visit to the site. It is difficult to provide a list of the type of data that should be collected, as this differs extensively from site to site, but one example is illustrated by the data collection form for phenological data specific to marked plants (Table 16.4). In order to maximise the benefit of this type of information, the vegetation ecologist should be able to form a picture in his/her mind about the site's important ecological processes, their functioning under different flow conditions and how they interrelate. It is also essential that the various zones within the riparian environment are clearly marked on a scaled cross-section containing heights above water levels and distances from the water's edge. These aspects are often not entirely elucidated during a single site visit, and require a number of visits at different times, particularly after events such as floods and freshes, or different low flow levels.

Photographs are taken of the site and transects from various angles at each visit. These provide a valuable record, as well as being useful reference material during the BBM Workshop.

Table 16.2 An example of a vegetation data sheet for completion at the BBM sites (based on information from Van Coller & Rogers 1996). MC - macro-channel; LHB - left hand bank; RHB - right hand bank.

RIVER : Thukela

BBM SITE No : 1 **CROSS SECTION :** C

CHANNEL TYPE : Pool - rapid

TAG NO.	SPECIES NAME	HEIGHT (m)	BANK	POSITION ON MC	SURFACE SUBSTRATUM TYPE	VERTICAL POSITION (m) *	LATERAL POSITION (m) **
1	*C. erythrophyllum*	7.5	LHB	Bank	Non-alluvium	8	17
2	*A. karroo*	7	LHB	Bank	Non-alluvium	7.5	16
4	*C. africana*	6.6	LHB	Bank	Firm alluvium	6.5	15
5	*Z. mucronata*	5.3	LHB	Bank	Firm alluvium	6	10
7	*S. mucronata*	1.2	LHB	Floor	Loose sand	1	2
8	*Phragmites* spp.	0.6-1.5	RHB	Floor	Gravel	0.5	1-2
9	*S. mucronata*	1.5	RHB	Floor	Mud	0.6	2.5
10	*S. mucronata*	1.8	RHB	Floor	Mud	0.7	3
11	*S. mucronata*	2.3	RHB	Floor	Mud	0.75	8
12	*C. erythrophyllum*	2.3	RHB	Bank	Loose sand	2	16
13	*C. erythrophyllum*	2.9	RHB	Bank	Loose sand	2.5	18

* is the vertical height above the lowest channel level on the profile.
** is the distance away from the river's edge or edge of closest channel

Table 16.3a Example of a completed collection form for river vegetation data.

RIVER VEGETATION DATA COLLECTION FORM	Recorder(s): Elton John	Sample No.: BBM 12 BE
Project & River Name: Orange	Date: 12/2/2000	Bank: N S [✓ E] W

Altitude: 1 846 m	Aspect: 110°	Reach type: Regime	Geology: Basalt	Landfacet: River
Latitude: 29° 11' 08" S	Longitude: 28° 33' 45" E	Fall angle: 16°	& Distance: 20 m	Photo No(s).: CB12

All measurements in meters (0.00 m)		Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
Name		Aquatic		Wet Bank Sedge		Wet Bank Shrub		Lower Dynamic		Shrub / Tree		Back Dynamic	
Sample area		0.5 x 10		1.5 x 10		4.8 x 10		6.1 x 10		6.5 x 10		2.4 x 10	
Tot. Veg. Cover %		5 %		80 %		75 %		90 %		90 %		60 %	
Litter Cover %		-		-		-		5 %		5 %		10 %	
Soil Depth		-		0.6 m		0.6 m		0.5 m		0.5 m		0.5 m	
Substratum Name		Cover %		Cover %		Cover %		Cover %		Cover %		Cover %	
Cobbles		30 %		9 %				1 %					
Boulders		< 1 %								20 %			
Sand		10 %		< 1%									
Silt		60 %		90 %		100 %		99 %		80 %		70 %	
Bedrock										< 1 %		30 %	
Actual end distance from water's edge (0.00m)		0.50-0.00 m		1.50 m		6.30 m		12.40 m		18.90 m		21.50 m	
Horizontal end distance from water's edge in m.		0.00 m		1.20 m		5.20 m		9.10 m		15.50 m		17.00 m	
Vertical end height above water level (m)		0.00 m		0.20 m		0.50 m		1.15 m		2.20 m		6.00 m	
Angle °		-		10 °		20 °		14 °		16 °		30 °	
Stratum 1 (Top)	Life form	Submerged herb		Herb		Tree		Shrub		Shrub		Shrub	
	Dominant species	Potamogeton pectinatus		Persicaria lapathifolium		Salix fragilis, S. babylonica		Artemisia afra		Artemisia afra		Rhus divaricata	
	Height & cover	0.2 m	1	1.0 m	1	3.5 m	3	0.6 m	+	1.2 m	4	2.0 m	+
Stratum 2	Life form	Floating herb		Sedge		Grass		Grass		Herb		Herb	
	Dominant species	Persicaria amphibia		Cyperus marginatus		Eragrostis curvula		Eragrostis curvula		Conyza sp.		Senecio harveianus	
	Height & cover	0.4 m	+	0.6 m	2	0.5 m	2	0.35 m	4	0.4 m	3	0.4 m	+
Stratum 3	Life form			Dwarf shrub		Herb							
	Dominant species			Salvia sp.		Rumex acetosella							
	Height & cover			0.25 m	1	0.2 m	3						
Stratum 4 (Bottom)	Life form												
	Dominant species												
	Height & cover												

Sketch, locality and additional notes:

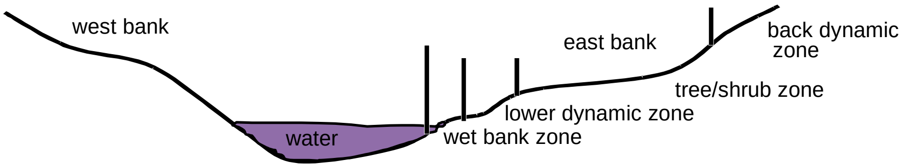


Table 16.3b Example of a completed data collection form for species in vegetation zones (see Boucher & Tlale 1999, for an explanation of the Braun-Blanquet Method).

Site No.:		**BBM 12 A E**			Cover value (% or Braun-Blanquet value)						
Coll. Nr.	No.	Species	Height	Phenology	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Notes
			00.00m		**Water**	**Sd**	**Shrub**	**LD**	**S/T**	**BD**	
	1	**Potamogeton pusillus**	**0.2 m**	**vg**	**R**						
	2	**Persicaria amphibia (6252)**	**0.4 m**	**vg**	**+**						
	3	**Cyperus marginatus**	**0.8 m**	**sd**		**2**	**1**				
	4	**Persicaria lapathifolia**	**0.9 m**	**fl**		**2**	**+**				
	5	**Rumex acetosella**	**0.5 m**	**gr**		**3**	**2**				
	6	**Gomphostigma virgatum**	**0.8 m**	**fl**	**R**	**R**	**R**				
	7	**Salix fragilis**	**0.9 m**	**vg**		**R**	**R**				
	8	**Panicum schinzii (6329)**	**0.6 m**	**sd**		**R**					
	9	**Pennisetum thunbergii**	**0.5 m**	**sd**			**R**	**2**			
	10	**Mariscus congestus**	**0.5 m**	**sd**		**1**	**R**				
	11	**Agrostis lachnatha var lachnantha**	**0.8 m**	**sd**		**+**	**+**				
	12	**Cyperus sp.**	**0.4 m**	**sd**		**1**	**3**	**2**			
	13	**Conyza sp.**	**0.7 m**	**sd**			**R**		**R**		
	14	**Salvia stenophylla**	**0.1 m**	**vg**		**+**	**R**	**+**			
	15	**Tagetes minuta**	**0.4 m**	**fl**			**+**	**R**	**1**	**1**	
	16	**Mentha longifolia**	**0.5 m**	**vg**			**+**	**+**			
	17	**Gazania krebsiana ssp. serrulata**	**0.4 m**	**sd**			**R**	**R**	**1**		
	18	**Pesudognaphalium luteo-album**	**0.6 m**	**fr**			**R**	**+**	**+**		
	19	**Senecio harveianus**	**0.6 m**	**fr**			**R**	**R**	**2**	**1**	
	20	**Gunnera perpensa**	**0.3 m**	**vg**			**+**	**R**			
	21	**Galium capense ssp. garipense**	**0.4 m**	**vg**				**+**	**+**		
	22	**Senecio sp. (6324)**	**0.5 m**	**vg**				**2**	**2**		
	23	**Rorippa nudiuscula (6283)**	**0.1 m**	**sd**				**R**	**R**		
	24	**Bromus catharticus**	**0.5 m**	**vg**				**R**			
6354	25	**Cirsium vulgare**	**0.6 m**	**fl**				**R**	**+**	**R**	
	26	**Artemisia afra**	**0.9 m**	**sd**				**+**	**4**	**2**	
	27	**Oxalis obtusa**	**0.2 m**	**vg**					**R**	**R**	
	28	**Mentha sp.**	**0.7 m**	**vg**					**1**	**1**	
	29	**Rhus divaricata**	**1.2 m**	**vg**					**R**	**1**	
6355	30	**Othonna sp.**	**0.5 m**	**vg**					**2**	**R**	
	31	**Eragrostis curvula**	**0.8 m**	**sd**			**R**	**4**	**4**	**+**	
	32	**Felicia mucronata**	**0.4 m**	**fl**					**R**		
	33		m								
	34		m								
	35		m								
Notes:											

Table 16.4 **Phenological data collection form (modified from Boucher & Tlale 1999).**

Locality: ……… Date:…………………………………………………

Plant identity: ……… Water depth (0.00m):.………………………

	Plant height 0.00 m	Distance from water	Stem elongation %	Leaf development condition %				Flower condition %				Seed (fruit) condition %			Plant dead	**Notes**: pollinators, seed dispersal agents, grazing, seedlings seen
				None	Enlarging	Mature	Falling	None	Buds	Open	Dead	None	Not ripe	Ripe		
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Special flow considerations

Several important points salient to different components of the flow regime need careful on-site investigation (see also Table 16.1).

Low flows during the dry season

Low flows are the primary source of the water required by the vegetation for transpiration, photosynthesis and growth. There is a distinct paucity of knowledge about the life cycles and functioning of most perennial riparian species, and particularly about their water requirements and rooting depths. Therefore, most low flow recommendations are based on the vegetation of the marginal zone and its water requirements. Mesic species exist in this zone, in close proximity to the water table of the riverbed. These species rely on very frequent, or continuous, direct contact with water. Recommendations on required low flows are based on understanding the relationship between this type of vegetation and low flow water levels.

Typical information required includes characteristics such as the permanence of the marginal vegetation and of the marginal zone itself. Some plants remain in specific areas within the marginal zone for many years. This is usually applicable to woody species (e.g. *Breonadia salicina* and *Salix mucronata*), reeds (e.g. *Phragmites australis*), large sedges (e.g. *Cyperus textilis*) or grasses with persistent and well-developed root stocks (e.g. *Arundinella nepalensis).* Some marginal species are more opportunistic, and continually shift position according to the seasonal flow levels. This is typical of many grasses such as *Cynodon*, *Imperata*, *Chloris* and the smaller sedges. Information about other characteristics also enhances understanding and correct interpretation of the factors impacting upon the vegetation. Such information could include:

- the extent of contact with the water (i.e. whether plants stand in surface water; the depth of that water; and whether or not this is a seasonal characteristic);
- the extent of utilisation of the marginal vegetation for grazing, reed cutting and so on.

In addition to direct botanical information, data about, and an understanding of, channel form and functioning are very important when assessing flow requirements. Examples of useful data include:

- the number of channels with flowing water;
- when these are likely to flow (perennially, seasonally, or ephemerally);
- the hydraulic control points that determine when seasonal and ephemeral channels flow;
- the presence of small backwaters, pools and wetlands, when these probably fill and the required frequency of replenishment;
- the nature of the substratum (e.g. fast-draining alluvial soils, clays, sand).

Freshes

Freshes are short-lived, high flow events of small magnitude, of most importance during the dry season.

The marginal zone or wetbank is inundated by freshes, and the upper limit of these flows defines the outer boundary of the marginal zone. Freshes ensure saturation of the marginal zone, and provide much of the sediments and nutrients that maintain the wetbank vegetation. Freshes also provide lateral flows into the adjacent riparian zone, refreshing small backwaters. The marginal zone needs to be inundated several times or regularly during the wet season.

Floods

Floods are high flows of longer duration and greater magnitude than freshes. Smaller ones occur occasionally during the wet season, and larger ones have return intervals of two or more years.

Floods are an important determinant of riparian functioning in that they:

- remove and translocate debris;
- recharge the macro-channel bank;
- deposit nutrients and sediments onto banks and floodplains;
- remove, with varying degrees of success, old, terrestrial and exotic plants;
- disperse seeds and propagules and turn over the seed bank;
- prevent infilling or “terrestrialisation” of the macro-channel floor;
- create space and new habitats for colonisation by riparian plants;
- provide the necessary substratum and groundwater conditions for the regeneration of species, and therefore aid maintenance of species diversity in the vegetation.

Assessment of flood requirements focuses on the whole riparian zone, that is, the entire macro-channel floor and the macro-channel bank. Accurate delineation of the riparian zone, and particularly its upper boundary, is very important for defining the extent of large floods and the relationship to processes determining their floral content. Confusion may result from distinguishing between the influence of water from the river itself seeping through the bank deposits versus runoff flows from the adjacent non-riverine terrestrial area. Evidence of previous flood levels is valuable for the assessment of flood sizes and frequencies, and should therefore be identified and noted.

Clues are sought of the relationships between floods of different sizes and frequencies, and the location of and variations in the species composition, density and height of the riverine vegetation. These will support recommendations for specific floods made later at the BBM Workshop. Clues about past floods may be obtained on site by the levels at which debris is found in the trees on the macro-channel bank, and debris lines in the transition areas between the riparian zone and adjacent terrestrial areas. These transitions are usually quite clear except in cases where anthropogenic actions, or previous very large floods, have disturbed them and a confused pattern of species distributions has resulted.

16.3.4 Data analysis

Soil samples are analysed for texture, content (e.g. pH, resistance, quantities of salts such as $NaC\ell$, $CaCO_3$, $CaSO_4$) and the percentage of organic materials present.

Using the total environmental data set from each zone (including soil characteristics, aspect, slope, height above water level), relationships between repetitive features in the vegetation and specific habitat features are sought. This type of analysis allows one to gain insights into factors causing changes in the vegetation.

From this, one can develop a predictive capacity about how changes in the flow regime are likely to induce changes in the vegetation. This approach would only apply when a number of sites have been examined. No direct comparison can be made using information from a single site, unless a database with similar information exists already and the information obtained from the site can be related back to this data set. However, good prior knowledge, from an experienced observer, of the effects of different flow regimes on the individual species and on the vegetation in a system, also does allow for intuitive evaluation of a site.

Techniques used to compare samples in the different zones may be either classificatory (e.g. using the Braun-Blanquet Method (Kent & Coker 1992; Werger 1974) or the statistical approximation of this technique, namely, TWINSPAN (Kent & Coker 1992); or by ordination (e.g. using Principal Components Analysis or Correspondence Analysis, or similar approaches as provided in the CANOCO (Kent & Coker 1992) or PRIMER (Clarke & Warwick 1994) analysis packages. A data matrix is constructed of the environmental and vegetation features of each transect sample in each zone on each bank, and relationships between vegetation distributions and environmental conditions are established. Data taken from all the BBM sites along the river are compared, to establish the different characteristics of each reach and the factors governing similarities and differences among them.

Scaled diagrams of each transect are prepared, to illustrate the vegetation features of each zone in relation to known discharges (and thus water levels). These are used in the BBM Workshop to predict the effects of flow modification, under the premise that each zone has certain characteristics which are related to the magnitude, timing, duration and frequency of flows that inundate it, and that these characteristics will change with changes in flow.

16.4 MINIMUM AND IDEAL DATA SETS

The minimum data set for a BBM site comprises the data collected during a single visit in the dry season. The data describe the species composition and cover of the dominant and emergent vegetation in the different vegetation zones along one complete transect. However, single transects provide no indication of within-site variability, and give data of unknown reliability for monitoring purposes. On the transect, the exact locations of zone boundaries are related to fixed known points, and the magnitudes of flow that would inundate these points are established. The different levels of inundation typical of wet and dry season flows are illustrated (e.g. on the annotated cross-section of the data sheet in Table 16.3a, and in Figure 16.1).

The ideal data set for a site includes information about all components of the vegetation, that is the algae, submerged macrophytes, lichens, mosses and higher plants. The composition and classification of the adjacent dryland vegetation is preferably also included in the data set to place the riparian vegetation within a local context and to identify non-riparian vegetation intrusions into the riparian zone. Information is collected from at least three complete transects, which are located to describe the main habitats present.

Desirable vegetation data include:

- composition of the vegetation at each sample point (a species list, as well as an indication of the cover and abundance of each species per zone (stratum));

- structure of the vegetation (the vegetation zones (strata) present, height measurements for each zone, dominant species in each zone);
- a horizontal digital photographic record of the vegetation in general, showing important features;
- a detailed, preferably vertical, photographic record of the vegetation in each zone, along each transect, so that changes in cover and location of individual species can be assessed;
- bimonthly samples of the algal flora, to reflect species variation and abundance;
- weekly information about the phenological performances (shoot lengthening, leaf stages, flowering, fruiting, dormancy and deaths) of selected component species, until important patterns for rivers in different climatic zones have been established. This information will influence flow release times.

Desirable data on the substrata include:

- classification of the percentage cover of the larger substratum types at each sample point;
- soil samples from each zone to determine:
    - the ratios of cobbles, pebbles, sand (coarse, medium and fine), loam and clay;
    - pH;
    - resistance;
    - sodium, calcium, chlorine, sulphate and sulfite concentrations;
    - percentage of organics;
- environmental characteristics, including slope and width of each zone, aspect, transect altitude and adjacent valley features;
- the upper and lower boundary of each zone above the mean dry season low flow level.

Notes are made of any human-related practices within and adjacent to the riparian zone, and the presence of any biota influencing the riparian vegetation is quantified as far as possible. A profile of each transect is drawn, to illustrate the relationship between habitat features, inundation levels and vegetation zones.

16.5 STARTER DOCUMENTATION FOR THE WORKSHOP

The aim of the chapter for the starter document is to summarise the available riparian vegetation data in a form that informs the other participants at the BBM Workshop on the characteristics of the vegetation and the riparian zone, as well as to provide simple summaries of the data collected. These summary data are referred to in the workshop when formulating recommendations on flow requirements for the vegetation component of the ecosystem.

A typical report covers the following topics.

- Introduction.
- Advantages and disadvantages of the selected BBM sites.
- Site-specific vegetation and physical characteristics of the sites (including a vegetation profile, description, vegetation table, and vegetation characteristics influenced by different flow regimes).
- Literature review of selected species and of their known flow requirements.

- An assessment of vegetation or environmental conditions that could change or be improved by different flow regimes.
- Conclusions.

Cross-section habitat data and vegetation data from the corresponding transect are integrated to produce the vegetation profile, using information from the surveyor and geomorphologist/sedimentologist. Plants are sized on the cross-section according to the cross-section scale. Various labels are added to the profile, such as species names, vegetation zone types, channel dimensions, or any other details that would assist in presenting the vegetation characteristics of the site (e.g. Figure 16.1). The vegetation profile provides a once-off look at the vegetation characteristics of the site, and has proven to be an exceptionally useful reference in previous BBM Workshops.

The vegetation table lists the important species at the sites, along with pertinent information for use in the workshop. Some of this information is obtained directly from the vegetation profile and the field data sheets, but it is in a user friendly format. As with the vegetation profile, this information has proven very useful in a number of previous workshops. (Tables 16.2, 16.3a & 16.3b, give examples of the kinds of information collected).

Further presentations of the data can take the form of an integrated Braun-Blanquet phytosociological table (e.g. see Boucher & Tlale 1999) and ordination diagrams (Figures 16.2a & 16.2b). Colour photographs and sketches are used for illustration. An appropriate graphics software package such as Microsoft Powerpoint or Corel Presentations is useful to produce the required vegetation profiles.

A review of appropriate literature should be undertaken for autecological and phenological information on the prominent, characteristic or indicator species present on site, if relevant data were not collected during the study. This information is invaluable for development of a predictive capacity regarding the effects of flow changes on riparian communities. The type of information required includes:

- the life history characteristics of prominent species, such as time of flowering, fruit production and seed set;
- whether the species are deciduous or evergreen;
- method of reproduction, that is by seeding, coppicing or a combination of the two;
- method of seed dispersal;
- typical spatial distribution characteristics;
- water use patterns;
- responses to changes in flow regime and flood events.

16.6 ROLES AND RESPONSIBILITIES AT THE WORKSHOP

The first part of a BBM Workshop is the site visit by the full team of specialists (Chapter 21). This helps develop a comprehensive understanding of the findings from many disciplines and focuses workshop participants on the task at hand. Links between the hydrological regime, local hydraulics, channel form and the distribution of physical habitats, and the vegetation zones are pointed out and discussed on site. As the instream and riparian vegetation, in turn, are an important determinant of faunal habitat, these links are also discussed.

During the workshop, the vegetation specialist assesses water requirements for the riparian vegetation, based on a combination of pertinent information sources:

- empirical evidence of links with the flow regime, collected during site visits (vegetation profiles, vegetation tables and site notes);
- available literature on specific plant species;
- commonly applied information on riparian vegetation, such as that of Van Coller & Rogers (1996);
- expert knowledge and experience of the specialist.

The process followed to describe the recommended EFR is detailed in Chapter 21. From a vegetation perspective, particularly in the Summer Rainfall Areas, it is often easiest - though not essential - to start the assessment at the beginning of the wet season, when increasing temperatures and photoperiod lead to increased water demands by the vegetation. In the Winter Rainfall Areas, or in areas where different levels of knowledge are available, it may be pertinent to start at other logical points, such as the end of spring or the start of the dry season, when many plants would be flowering.

Important aspects to consider when an EFR is being set in the workshop are discussed below. It should be remembered that the diversity of riparian vegetation is driven by variability in flow regimes. The more variable the flows, the greater the diversity.

16.6.1 Low flows

Low flows play an important role in the completion of life cycles of riparian and aquatic plants. Plant species are identified that are dependent on low flows to complete critical parts of their life cycles. Some species, for instance, may depend on certain flow conditions to stimulate flowering. Particular attention is paid to key or critical species, for example, ones that are sensitive to changes in flows or moisture regimes, are long-lived riparian specialists, or are socially or economically important. Consideration is given to what would happen to these species if low flows continued for an abnormally long period, or if flow ceased. It is sometimes necessary to consider what would result if natural low flows were replaced with abnormally constant higher flows, as could happen, for instance, with the release downstream of irrigation water. The number or cover of individuals and species might change, and this could affect channel morphology in the long term through, for instance, vegetation encroaching and blocking the channel. On the other hand, vegetation cover could be lost, leading to bank erosion and land loss.

16.6.2 High flows

All envisaged effects on flora and vegetation associated with high flows are considered. Such flows could reduce salinity levels or nutrient accumulations, change water temperatures, open up densely vegetated channels, distribute seeds and diaspores down channel, and much more. Where possible, the effects are linked to different magnitude high flows.

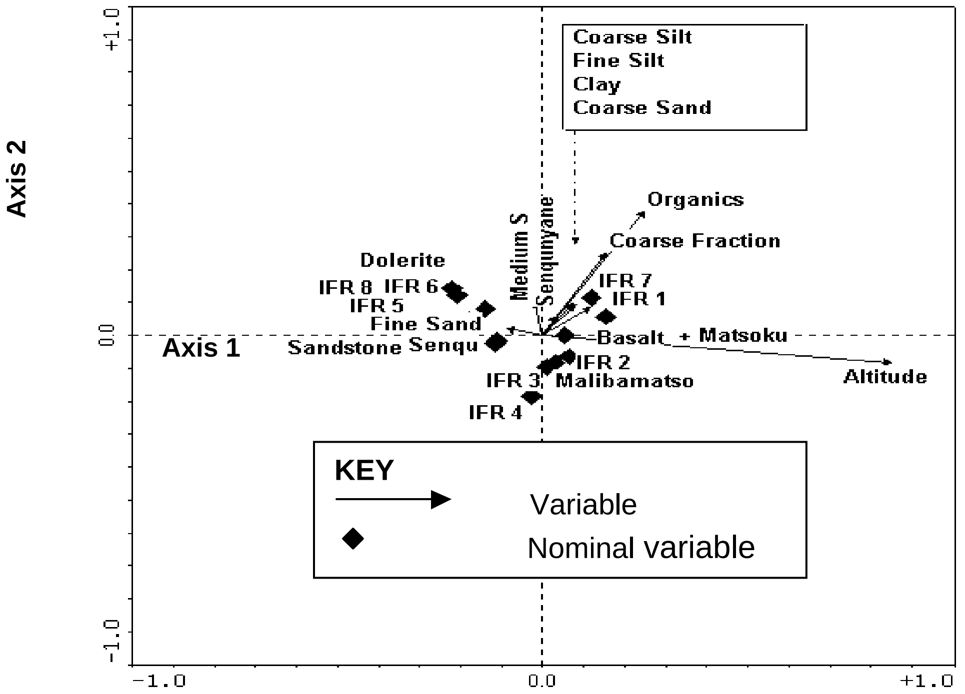


Figure 16.2a Lesotho Rivers IFR study: canonical correspondence analysis biplot (axes 1 & 2) using altitude, soil organics, geology and locality as nominal variables; soil texture as compositional data (log-transformed); and all available species data excluding algae (from Boucher & Tlale 1999). IFR 1-8 represent the BBM sites.

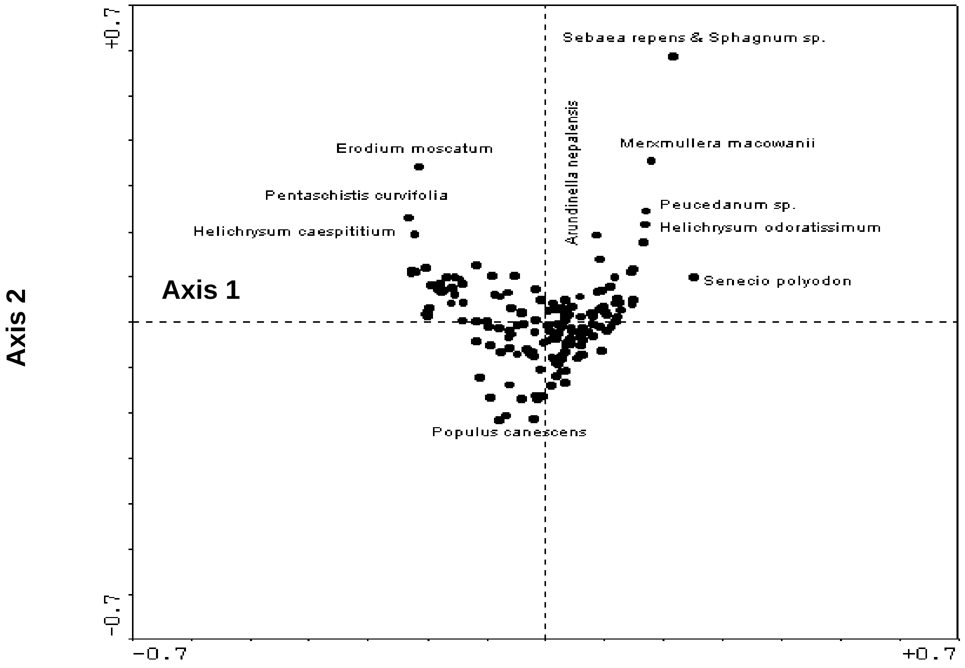


Figure 16.2b Lesotho Rivers IFR study: canonical correspondence analysis biplot (axes 1 & 2), illustrating the distribution of species in relation to the environmental factors as shown in Figure 16.2a (from Boucher & Tlale 1999).

Establishment of some tree elements is associated with rare periodic events, such as particularly long wet seasons or floods that bury seeds and/or clear areas of vegetation thereby stimulating germination. The 1:50 year or larger floods can radically modify river channels and riparian biotas, resulting essentially in a 'new-look' river and riparian zone.

A reduction in high flows through droughts or dams harnessing floods, can cause banks to be drier than normal. This condition is conducive to hotter than normal fires that have a destructive effect on heat-sensitive, indigenous riparian trees and shrubs.

Before or at the start of a new wet season in Summer Rainfall Areas, there is an increased water demand from some riparian species in response to increasing transpiration rates, growth of new leaves, roots and flowers and germination of seeds. This water is provided by riverbanks or aquifers (Chapter 19), which need to be recharged by early wet season surges of high flow. These areas are recharged at different rates, depending on the soil types, the layering of the soil and the extent of the previous dry period.

In the Summer Rainfall Area, most perennial plants react to the general increase in moisture conditions at the onset of the rainy season. When monitoring riparian plants and assessing the effects of increased flows, the effects of increased soil moisture in the banks from rain need to be distinguished from the effects from higher flow levels. The situation is further complicated by some plant species responding faster than others to slightly elevated river flows, following the onset of the rainy season. It is essential to understand the reactions of different species, when assessing EFRs for the riparian vegetation as a whole. In the Winter Rainfall Region the above effect is less critical, because cold winter temperatures associated with the rain retard or negate the plants' reactions to increased moisture conditions.

When considering the effects of reductions in high flows, it is essential to remember that a reduction in a "keystone" species, by definition, means that the whole system is exposed to an adverse chain reaction. Additionally, systems under stress from, for instance, flow reductions, are more susceptible to invasion by elements of exotic vegetation. These can further and drastically change the ecosystem as a whole.

16.7 ROLES AND RESPONSIBILITIES AFTER THE WORKSHOP

The most urgent task after the BBM Workshop is to collect any data necessary to fill critical knowledge gaps. The specialist should distinguish between longer-term data needs and information that can be collected within the short term.

Production of the amended starter document report on vegetation for presentation to the client is the next critical stage. In this report, positive beneficial aspects of the study should be emphasised and knowledge gaps indicated. Publication of results from the study, in an accredited publication, remains the specialist's responsibility to the scientific community, but is dependent on the client's approval.

16.8 EXAMPLE OF TERMS OF REFERENCE

Typical Terms of Reference for the vegetation component of the BBM are as follows.

- Locate all existing or available information on riparian and aquatic vegetation in the catchment, including the aerial video, aerial photographs, reports and publications. Write a literature review.
- Undertake a field visit, with other selected specialists, to identify BBM sites with vegetation suitable for a study using the BBM.
- Describe, and quantify to the extent possible, the important vegetation components present at the selected BBM sites. Relate these to the macro-channel and water, using survey diagrams, surveyed cross-sections, vegetation transects and other appropriate methods. Ensure that the location, species and sizes of the main vegetation components and zones are recorded.
- Identify important and appropriate riparian species at the sites that could be used to guide flow recommendations, and describe their flow-related needs.
- Ensure that all important and appropriate plant species, vegetation communities and zones are tagged and included in the surveyed cross-sections.
- Prepare a report on the vegetation study for inclusion in the workshop starter document.
- Attend the BBM Workshop and make appropriate contributions and recommendations towards the formulation of the EFR for the river.
- Attend any follow-up Scenario Meetings (Chapter 22), and make appropriate input regarding the consequences for the vegetation of any other potential flow regime(s).

16.9 MINIMUM AND OPTIMUM SPECIALIST TRAINING

The same specialist should undertake all aspects of the study and attend all the specialist meetings. This specialist should be a vegetation ecologist with at least a M.Sc. degree, and specialist knowledge of riparian and aquatic vegetation. He/she should have a good understanding of vegetation dynamics, particularly in response to changes in flow regime, and of distribution patterns and associated determinants. He/she should also be experienced in the management of riparian vegetation. The specialist should preferably have examined the selected BBM sites over a range of discharges, so that the distribution of vegetation in relation to the flow regime is understood. There should also be a technical assistant, preferably with a B.Sc. degree (with Botany as a major) or with adequate Technikon training.

Sampling and identification of algae and diatomaceous flora is a highly specialised task, and should be undertaken by a botanist with pertinent specialist training.

16.10 POTENTIAL PITFALLS

Often the choice of BBM sites is made during the dry season, but a serious assessment should be made of their accessibility during all seasons.

At a site, the exact position of vegetation features should only be surveyed in after each transect has been examined botanically, otherwise key features might be overlooked. All the required detail then can be included in the survey, and also entered on the vegetation data collection forms. The vegetation scientist obtains topographical measurements from the surveyor, preferably directly on site to ensure their completeness. Alternatively, the identification numbers of the land surveyor's relevant coordinates identifying each vegetation measuring point should be noted on the botanical data collection sheets as they are recorded.

All boundaries between vegetation zones should be permanently marked, so that measurements and recordings taken during subsequent visits in different seasons can be accurately related to one other. High quality, permanent markings are an excellent investment, as the surveyed transects are invaluable tools for monitoring long-term change. Inadequate marking of sites, or the loss of marks through gross environmental change or mischievous actions by independent parties, seriously reduces the value of each transect.

It is critical that water depth is recorded and the inundation level relative to boundaries between the vegetation zones or location of marked species noted, each time botanical data are recorded at a site.

Natural or artificial destruction of parts of the sites can occur, and so it is wise to apply the precautionary principle and examine more rather than fewer sites. The examination of a number of sites also provides more substantive interpretations, whereas sparse information lowers the reliability of any interpretation.

Lack of sufficient, general long-term data about the successional reactions of vegetation to flow regimes, leads to inadequate interpretation and appreciation of different conditions in the river. Continued research is needed to increase the knowledge base in this field.

16.11 FURTHER DEVELOPMENTS

An expert system should be developed containing sufficient botanical aspects to provide consistent, predictive evaluation of the responses of flora and vegetation to different flow regimes. This should evolve from long-term monitoring of riparian species, experiments and modelling studies. The approach requires the simultaneous modelling of spatial and temporal responses of plants to their environment. Current knowledge about the processes that drive the dynamics of riparian vegetation in the short term could be linked with long-term climatic data, and used to facilitate the development of management scenarios that would systematically investigate the interactions between all relevant factors and their logical consequences. An important advantage of this type of simulation model is the use of rules rather than mathematical equations to include necessary biological information. When tackling complex problems, such as riparian response to changing flows, this type of model allows the direct inclusion of expert knowledge, and is not restricted to the use of hard data. The combined approach of long-term field research and carefully constructed simulation models has the potential to gain the best possible understanding about natural long-term vegetation dynamics and the possible consequences of anthropogenic impacts.

16.12 MONITORING

The following description is for flowering plants, ferns and mosses. Algal and diatom floras require special methods that are not dealt with here.

A digital photographic record of the site in general, of each vegetation zone and of specific indicator plants will give a more reliable and directly comparable statistical indication of degree of change than conventional photographic methods. GIS mapping techniques can effectively be used for this type of monitoring.

Very little information exists in the South African literature about the responses of plant species to fluctuations in water level or to changes in water quality. This is a critical gap in our knowledge, and efforts need to be made to systematically enhance the knowledge base. One way of doing this is to mark a number of individual plants of a number of critical or important species, located at different distances from the water's edge at the BBM sites. Data on each should be collected on a regular basis through the year. On each visit, the phenological state of the plants should be noted. Responses related to differences in climate can be eliminated through this type of study, because each site is specific to a particular climatic regime.

16.13 CONCLUSIONS

Detailed information about the vegetation component is a critical element in EFR determinations. It provides a knowledgeable observer with long-term, medium-term and short-term insights into the condition and character of a river and, therefore, also of how the river is likely to change with modifications to the flow regime.

Southern Africa has an urgent need for the establishment of long-term monitoring sites to assess vegetation change and the relationship of this change to changes in flow regimes.

17. AQUATIC INVERTEBRATES

Jay O’Keeffe and Chris Dickens

17.1 AQUATIC INVERTEBRATES IN RIVER STRUCTURE, FUNCTIONING AND MANAGEMENT

Aquatic invertebrates, in the sense used in applications of the BBM, are those insects (often in larval form), worms, molluscs and crustaceans that are found on the riverbed or along the channel margins. Their forms, life histories, and ecological and habitat requirements are so numerous and diverse, that these communities have been more commonly used than any other biotic group to characterise and monitor river condition. In addition, they are small and relatively immobile, so they can be collected easily. However, they are often difficult to identify to species level, because of their small size and the minor differences between them. Also, the South African taxonomy of some groups, such as the ubiquitous Chironomidae, is still incomplete. For those wishing to study invertebrates, a partial solution to these problems has been the development of indices for monitoring activities that require identification only to family level. The SASS4 Method (Chutter 1994, 1998) provides one such index, and trades off a loss of information at finer taxonomic levels against simpler identifications that require less time and fewer additional resources.

Invertebrates play a major part in river functioning. They are responsible for retaining and breaking down organic material, recycling minerals and nutrients, and contributing to energy processing in the river at different trophic levels. Most benthic invertebrates are detritivores, although some are herbivores and some, such as dragonfly larvae, are carnivores. Other, probably lesser, effects, include the transport of organic material into and out of the river (through emergence, egg laying, and for animals such as crabs, riparian feeding and aquatic defaecation), and structural activities such as case building and gluing or enmeshing small particles of silt and sand. Burrowing invertebrates, such as worms, may be important in aerating sediments and releasing nutrients.

Invertebrates appear to be less important in the direct mineralisation of organic matter, than in its initial breakdown and inoculation with microflora. Fisher & Likens (1973) found that invertebrate respiration in a small mountain stream amounted to only 0.3% of energy output, whereas the respiration of microorganisms contributed 34%. Cummins (1979) suggested the following four functional feeding groups to describe the contributions of invertebrates to energy and nutrient processing: shredders; collectors, grazers, and predators. The River Continuum Concept (RCC) of Vannote *et al.* (1980) proposed that shredders such as stonefly larvae should dominate headwaters, where coarse organic material from overhanging trees is the main energy input. In the downstream wider, more open middle reaches, grazers (e.g. some mayfly nymphs) and collectors (e.g. blackfly and hydropsychid caddis larvae) should dominate. The latter groups exploit the benthic primary producers and the finer organic material emanating from the upper reaches, respectively. Finally, in the turbid lower reaches of large rivers, collectors of fine particulate material and phytoplankton such as oligochaete worms and bivalve molluscs, should be the most abundant components of the community. In this model, predators are seen as a more or less constant proportion of the community, though the species composition changes in different parts of the river. Research in South African rivers (King *et al.*, 1988; Palmer & O'Keeffe 1992; *inter alia*) has generated mixed reviews regarding the details of the RCC, but the basic hypotheses may be considered to have validity in rivers with the basic characteristics to which Vannote *et al.* (1980) refer.

17.2 AQUATIC INVERTEBRATE STUDIES IN THE BUILDING BLOCK METHODOLOGY

In the BBM, aquatic invertebrates are used, together with fish (Chapter 18) and riparian vegetation (Chapter 16), as the main biotic indicators of the flow requirements for a river reach. A specialist can use knowledge of the diversity and abundance of invertebrates in the different habitats during different seasons, to advise on what kind of flow conditions would be necessary to maintain or improve the health of the river in relation to the designated EMC and objectives (Chapter 11). The kinds of information used are described in Appendix 17.1. Maintaining the biodiversity of invertebrate communities is also important, and setting flows to optimise their natural diversity and abundance is an aim of the BBM. Additionally, although the BBM is predominately designed to assess the water quantity requirements for rivers, it recognises the link between discharge and water quality through a water quality component (Chapter 15). Invertebrates respond sensitively to changes in water quality, and indices reflecting their responses, particularly to organic pollution, have been in use in river ecology since the early 20th Century. In South Africa, such an index is SASS4, developed by Chutter (1994) and now extensively used for biomonitoring purposes. Mainly designed to reflect on the status of the river in terms of organic enrichment, SASS4 also provides a general picture of river health, particularly if interpreted in relation to habitat availability. In the BBM, SASS4 is used to aid assessment of the PES, setting of the EMC, and as a check of the results being produced from the water quality assessment.

The invertebrate specialist needs to be able to understand the underlying concepts of the SASS and have a wide experience of invertebrate ecology. Clues need to be gleaned from the fieldwork and data on which taxa are flow-sensitive, how the fauna is distributed and why, which can recolonise quickly after dry periods and so on. For instance, the diversity and abundance of wetted habitats are major determinants of the composition of invertebrate communities. For example, a sand bed river under low flow conditions that do not inundate the channel margins will have only two physical habitats - the water column and the sandy bed. The resulting invertebrate community will be sparse and impoverished. In comparison, a multi-channel riverbed under higher flows, with riffles, runs, pools, inundated marginal vegetation and backwaters, will have a complex mosaic of physical habitats and a more diverse invertebrate community. The expected invertebrate communities, and therefore the flows recommended for their maintenance or reinstatement in the river, will thus depend on the diversity and abundance of available habitats.

Similarly, different invertebrate species have very different tolerances to conditions of zero flow or no surface water, and recolonise after dry conditions at different rates. Some chironomids and many molluscs can survive dry conditions, but the chironomids, able to emerge and fly to new habitats, recolonise formerly dry sites more quickly than do the molluscs. Many mayflies cannot persist for long under no-flow conditions, even where there are permanent pools. O’Keeffe & Uys (1998) found that temporary rivers may harbour communities at least as diverse as permanent rivers over the whole year, because they will have different invertebrate groups in non-flowing and flowing periods. However, the diversity at any one time is likely to be lower in the temporary river, unless it has been flowing for a prolonged period. It seems that three months of continuous flow is adequate to allow the recolonisation of most invertebrate species (Harrison 1966; Weeks *et al.,* 1996; among others). The presence of refugia, such as constantly flowing tributaries, may also influence the rate of recovery of the biota from no-flow conditions. Thus, the flow conditions prior to invertebrate sampling will have a considerable effect on the communities found, and the invertebrate specialist will have to interpret the results and make recommendations with this in mind.

Invertebrate data, when collected and used properly, can therefore be used to help identify a range of flow-related conditions that might be desired. Invertebrate and fish data are generally used to determine required types of habitats and hydraulic conditions, and the invertebrates are also used to indicate the vulnerability of the biota to water quality changes.

17.3 SEQUENCE OF ACTIVITIES

Once the general study area has been defined (Chapters 6 & 7), the following actions should be taken.

17.3.1 Access relevant historical data

- Complete a literature search for historical data on invertebrate surveys of the river, in order to ascertain temporal and spatial distributions of species, and linked data on chemical and physical variables and hydraulic habitats.
- Locate similar historical data from rivers in similar ecoregions.
- Investigate national and regional invertebrate databases for similar data.

17.3.2 Collect invertebrate data

- Identify sampling sites. These may not necessarily be at the BBM sites if, for instance, better habitat is available elsewhere. However, the sampling sites should be sufficiently close to BBM sites to be visited on the workshop field visit, and should be representative of the river zone being assessed.
- Collect invertebrate samples in each major habitat at each site, preferably at least once during the wet and the dry seasons. Record associated habitat information and water quality conditions. Major habitats can be distinguished using Rowntree & Wadeson's (1999) description of hydraulic biotopes. Habitat and water quality information should include recording at least the following variables: EC, pH, temperature, DO, turbidity (Chapter 15), and a note of the habitat sampled.
- At each invertebrate sampling point, measure average (0.6-depth) velocity, water depth and substratum particle size, and record available hydraulic and overhead cover.
- Identify the specimens in each sample to species level where possible, and identify from the literature the critical or sensitive species from a flow-related perspective, for each habitat (e.g. Appendix 17.1).

17.3.3 Analysis of the data for the workshop

- Calculate SASS4 scores (at the family level), or identify invertebrates to more detailed levels of taxonomic resolution if resources and expertise are available. Also calculate the associated habitat scores, using a method such as the Integrated Habitat Assessment System (IHAS Version 2) of McMillan (1998).
- Describe the Reference Condition for each BBM site or reach, either from historical data or from comparable catchments.

- Categorise the PES (Class A-F; see Chapter 4), and compare with the Reference Condition, in order to assess how far the river has changed from its natural condition.
- From measured and historical data, describe hydraulic conditions associated with each sensitive species. Use this to recommend flows that will provide for the conditions specified in the EMC and objectives for the river (see Chapter 11).

17.3.4 The workshop

- Prepare a report for the starter document for the BBM Workshop (Section 17.5).
- At the workshop, define an EMC (A-D) and objectives for the flow-related management of the river that will maintain the invertebrate fauna in that class.
- Use the data on hydraulic tolerance ranges, particularly for sensitive species, combined with the cross-section data, to recommend maintenance and drought flows for critical months in order to maintain the invertebrate fauna within the recommended EMC.

17.4 MINIMUM AND IDEAL DATA SETS

The basic data set for use in an application of the BBM will be drawn from a survey of the invertebrate fauna of all habitats at all BBM sites, with the animals identified to family level or to more detailed levels (Section 17.3.3). This data set is used to assess the present state of the river, and to recommend flows which will maintain or improve the river according to the EMC and objectives.

The data set can be created during the preparation phase for the BBM Workshop, and can suffice on its own to provide clues on which to base flow requirements, albeit at low confidence. A single survey inevitably provides an incomplete picture of invertebrate communities, because many families will be missed or not sampled representatively, and the data reflect community composition for only one season. However, since many of the clues for setting flow requirements are based on the types of habitats available in the river at any one discharge, the overall communities can usually be inferred from an inventory of the available habitats. In addition, there are now databases available for most parts of the country (e.g. at the Albany Museum, Grahamstown, and the Biobase of Dallas *et al.*, 1999), from which to extrapolate the likely communities in most South African rivers. The main limitation in carrying out an EFA based on only one survey at family level, is that inadequate information on critical or sensitive species will be collected. This is important, because flow recommendations are often set in relation to the habitat and hydraulic needs of these species, on the assumption that if their requirements are met, so will those of the rest of the community.

An ideal data set of invertebrates for an application of the BBM would be as follows.

- Historical data sets of the invertebrate fauna of each river zone, from all habitats, during all seasons, preferably before man had significantly impacted the river. The invertebrates would be identified to species level where possible, and relative abundances recorded for each species. Such a data set provides a Reference Condition against which to judge subsequent changes. However, it cannot be created for a BBM assessment unless the river is presently unimpacted - for impacted rivers, it either will or will not exist.

- Present-day data sets for each BBM site, at the same level of detail as above, from which to assess the PES of the river.
- Quantification of the ranges of tolerance for hydraulic habitat of selected sensitive species from each habitat, in terms of velocity, depth, substratum type and cover. This information, together with the cross-section data, will allow identification of discharges at which community changes are likely to take place.

Even with information of this calibre, uncertainties will remain as to the requirements for critical lifestages of species, such as the breeding and egg laying stages. It is not possible usually to collect such detailed biological information within a BBM study, but such data should be compiled gradually on a regional basis, to act as general reference data for EFAs.

17.5 STARTER DOCUMENTATION FOR THE WORKSHOP

The invertebrate chapter of the starter document is intended to be a summary of the information collected and listed in Section 17.3. It provides the perspective of the invertebrate specialist, for examination by the other specialists at the BBM Workshop, and acts as a reference document for the invertebrate specialist during the workshop. It also serves as a reference document on the river, for the author of the workshop report and for anyone revisiting the results of the workshop at a later date.

The starter document should, therefore, contain the following information.

- A review of the literature and databases pertaining to invertebrates for the river being studied. This should be a summary of the information available, interpreted in terms of the historical condition of the river. It should include an assessment of the level of detail available, the confidence in its accuracy and the confidence in the interpretation of the data.
- An assessment of the Reference Condition of the study area in terms of invertebrate communities. This should be inferred from data on similar rivers, if no direct information is available. The Reference Condition should include a description of any species not currently found in the river but expected to be there, and should identify possible reasons why the present invertebrate community might change, such as a deterioration in water quality or change in habitat structure.
- An assessment of the PES of the invertebrate communities, in terms of:
    - a description of the sites and habitats surveyed;
    - a description of the data collection methods used;
    - a list or summary of the species found in each habitat at each site;
    - an analysis of the SASS4 results.
- Identification of any flow-related critical or sensitive species and their habitats. These act as indicator species, and information on their tolerance ranges will be the most common data used to describe flow requirements for maintenance of the desired invertebrate communities.
- An analysis of the tolerance ranges of these species and communities, in terms of the depths, velocities, substratum types and cover conditions in which they were most commonly found, or at which the maximum natural diversity of species occurred.

At the workshop, the information in the starter document is initially used to help the specialist group define a recommended EMC (from A-D), and to set specific objectives for the management of the river to maintain the invertebrate communities linked to that EMC.

Once the EMC and specific objectives are set (e.g. to prevent increases in pest blackfly, or to maintain the SASS4 scores within a specified range), the invertebrate specialist should use the information in the starter document to recommend flows as per BBM procedures. These will be flows that will maintain or create habitat conditions, and thus should ensure the maintenance or achievement of the EMC and related objectives.

17.6 ROLES AND RESPONSIBILITIES AT THE WORKSHOP

At the BBM Workshop, the invertebrate specialist is responsible for the interpretation of each step of the process of recommending the EFR, in terms of the implications for the invertebrate communities.

The workshop begins with a visit to each BBM site, at which some additional sampling may take place, especially if the season and/or water level are different from when the previous samples were collected. Such sampling will seldom be more than a cursory survey at the SASS4 level. At each site, the invertebrate specialist summarises conditions and PES in terms of the invertebrate fauna, and points out special features such as critical habitats.

During the workshop sessions, the invertebrate specialist states the PES, with reasons, contributes to the assessment of ecological importance and sensitivity (Kleynhans 1999a; Chapter 10) and recommends an EMC and objectives from the perspective of the invertebrates. The EMC recommended by the specialists will be a consensus one based on the ecological importance and sensitivity rating, the PES, and their opinion of what improvements are achievable. The final assignment of an EMC is the responsibility of the Minister (or his/her nominee), taking into account the recommendations of the specialists and the wishes of stakeholders (Chapter 4).

The definition of a flow regime to meet the above objectives is then addressed. Instantaneous discharge is considered month by month, and in terms of baseflows and higher flows for maintenance and drought conditions (see Chapter 5). The invertebrate specialist defines the limiting requirements for each of these categories of flow, with reference to the objectives for maintaining the invertebrate communities. For example, the baseflow objective for the driest month in drought conditions might be to maintain a minimal flow through riffles, to allow the survival of rheophilic species such as hydropsychid caddis larvae. The invertebrate specialist, using the information from the summary chapter in the starter document or accompanying data set, defines this required condition in terms of depth, velocity and wetted perimeter. The hydraulician converts these requirements to a discharge, referring to the cross-section data (Chapter 13). Similarly, higher flows during maintenance years might be required to scour silt from cobbles in riffles, in order to maintain habitat for invertebrate riffle dwellers. In this case, the invertebrate specialist and the geomorphologist work with the hydraulic modeller to define flow conditions to achieve this objective. If the discharge recommended by the invertebrate specialist for a particular month and category of flow meets the requirements for all the other ecosystem components, then this discharge becomes the recommended one for that part of the modified flow regime (the EFR). In such a case, the invertebrate specialist becomes the primary motivator for the discharge and provides, as precisely as possible, a written motivation. This details the reasons for the recommended discharge, and explains why it should be no lower.

The core of the workshop is the discussion by the various specialists. Consensus must be reached as to the discharge that will reasonably meet the needs of all ecosystem components for each category of flow, each month, during maintenance and drought years. Each specialist also assesses the suitability of each site for the task of setting an EFR, and the confidence of the resulting recommendations.

A special case for which the invertebrate specialist is often required to make the main input is when unseasonally high baseflows are being released from a dam, perhaps to meet downstream irrigation demands. To prevent undue ecosystem degradation, a “capping flow” recommendation may be made, which is designed to prevent artificially high, stable flows during the dry season. By overriding the natural variability of the flow regime, such flows could create suitable conditions for one or a few species that could then increase to pest proportions. For instance, such conditions have been created in the Orange River below the Van der Kloof Dam, in the Vaal River below Vaal Dam, and in the Great Fish River below Grassridge Dam (e.g. O’Keeffe & De Moor 1988). In each case, the result has been an invertebrate fauna seasonally dominated by large swarms of the blackfly, *Simulium chutteri*, the adult females of which are blood feeders on farm stock. The capping flow recommendation should aim to prevent such seasonal reversals of discharge magnitudes, and to ensure a more natural and balanced invertebrate community through continuation of natural flow variability.

17.7 ROLES AND RESPONSIBILITIES AFTER THE WORKSHOP

All the specialists are required to check the flow recommendations and the motivations in the report of the BBM Workshop (Chapter 21), and may be required to participate in the following Scenario Meetings (Chapter 22).

Following the workshop, the recommended EFR is entered into a yield model as one of the user requirements for the water resource. As there are always limits to the possibilities for flow management (depending on storage capacity and other demands for water), the results of yield modelling may indicate that the EFR can only be met for a certain percentage of time. A number of scenarios may be developed, each depicting a different mix of user demands, the consequent yield, and the degree to which the recommended EFR is met. The role of the invertebrate specialist is to examine these scenarios, and to assess the ecological implications for invertebrates and their habitats of any failures to meet different flow components of the EFR. Together, all the specialists in the BBM team then rank the scenarios in terms of the severity of their ecological consequences. For example, one scenario may describe a reduction in the level of minimum drought flows, whilst another describes an extension of the period of drought flows, but at the recommended level. The assessment of which scenario is likely to be more damaging to the invertebrate communities will probably be qualitative. It is nevertheless necessary, at least in the short term, so that planners can proceed with compilation of the operating rules for the planned dam.

17.8 EXAMPLE OF TERMS OF REFERENCE

The invertebrate specialist undertakes a number of tasks, usually within a period of six to ten months from the start of the project. The approximate number of working hours allocated to each task is shown below. This will vary, however, depending on the level of detail required for any project, the information already available, the size of the study area, and the number of sites. These approximate figures are for 200 km of river with four sites. They should be seen as minimum time allocations, and do not allow an investment into new understanding or techniques.

17.8.1 Literature search

The first task (32 hours) is to carry out a literature search for historical invertebrate surveys of the river, to identify other historical data from rivers in similar ecoregions, and to research national and regional invertebrate databases, in order to obtain as complete a description as possible of the invertebrate communities that would be expected and those that have been found in the river.

17.8.2 Choosing invertebrate sampling sites

The second task, requiring about eight hours, is to identify invertebrate sampling sites. These may not necessarily be at the BBM sites, but should be sufficiently close to be visited on the workshop field visit, and should be representative of the river zone being assessed.

17.8.3 Invertebrate sampling

The third task, that of invertebrate sampling, requires approx. 96 hours plus travel time and involves the following steps:

- Pre-workshop invertebrate sampling at each site, preferably at least once during the wet and dry seasons. All available (i.e. wetted) major habitats should be sampled. Standard SASS4 sampling methods are used, but more detailed sampling should be undertaken if time and resources allow. The associated habitat information and water quality conditions should be recorded.
- At each invertebrate sampling point, average velocity, depth and substratum particle size are measured and the cover types available are recorded.
- Each sample should be identified to species level where possible, and from the literature (e.g. Appendix 17.1) the flow-related critical or sensitive species for each habitat should be determined.
- The SASS4 scores for each sample, and associated habitat scores, should be calculated.

17.8.4 Defining the Reference Condition for invertebrates

The fourth task (16 hours) is to describe the Reference Condition, either from historical data or from comparable catchments. The expected invertebrate communities and habitats under the Reference Condition should be detailed, and those species/families which are expected to be in the river, but have not been found should be listed.

17.8.5 Assessing the Present Ecological State

The fifth task, requiring about 8 hours, is to assess the PES (Class A-F) in terms of the difference between the Reference Condition and present survey results. The assessment should consider species or groups either missing in the present condition, or overabundant compared to the Reference Condition, and a comparison of SASS4 scores.

17.8.6 Recommending hydraulic conditions to achieve the Ecological Management Class

The sixth task (16 hours) is to describe measured depths, average velocities and substratum types most commonly associated with sensitive species and families, and/or with maximum biodiversity. This should be combined with literature information to recommend conditions that will meet the designated EMC and ecological objectives.

17.8.7 Producing a report for the starter document

The seventh task (24 hours) is to prepare a chapter for the workshop starter document, as per Section 17.5.

17.8.8 Attending the workshop

The eighth task, attendance at the BBM Workshop, requires a total of about 40 hours, plus travel and accommodations costs. The specialist is required to assist with or carry out the following activities:

- attend site visits and present a summary of conditions relevant to invertebrate distributions at each site;
- define an EMC (A-D) and objectives for the flow-related management of the river to maintain the invertebrate fauna in that EMC;
- use habitat preference data, particularly for sensitive species, combined with the cross-section data, to recommend maintenance and drought flows for critical months in order to maintain the invertebrate fauna within the recommended EMC;
- write motivations for each of the recommended flows.

17.8.9 Checking the workshop report

When the workshop report is produced, the draft should be checked for accuracy and for the inclusion of all the recommendations regarding invertebrates. Approximately four hours are required for this task.

17.8.10 Attending the Scenario Meeting(s)

The final task, which is allocated approx. 12 hours, is to attend the Scenario Meeting(s) if required. Critical assessment of the effects of a range of potential flow scenarios on the invertebrate communities should be provided, particularly in relation to the EMC and its related objectives.

17.9 MINIMUM AND OPTIMUM SPECIALIST TRAINING

In most parts of South Africa, there is one or more experienced aquatic ecologist with knowledge of the taxonomy and distributions of riverine invertebrates. Such a person is typically well qualified (usually with a Ph.D. degree), with at least ten years experience of field studies, and a detailed knowledge of the local rivers. This is the ideal type of specialist for a BBM assessment, since the process requires input from experienced ecologists. This is needed when providing the often subjective judgements involved in describing Reference Conditions, recommending EMCs, and deciding on the appropriate flow regime to achieve an EMC.

The requirements of the new Water Act in terms of the ecological Reserve (Chapter 4) have substantially increased the demand for trained river ecologists. It is therefore unrealistic to rely on an unlimited supply of experienced specialists as described above. Speed training of suitable extra invertebrate specialists who can contribute to EFAs, could be achieved by ‘twinning’ an experienced specialist with a trainee during actual applications of the BBM. The minimum requirements for such trainees would be a university degree in the biological sciences with a good grounding in general ecological theory and in river ecology. Such trainees would quickly grasp the concept of matching the invertebrates with their environmental and habitat requirements, and understand the suite of conditions necessary for the survival and persistence of each part of species’ life cycles. There is no ‘cookery book’ recipe for compiling EFRs, and therefore a sound background understanding of river processes and life history requirements of aquatic invertebrates is a prerequisite. In addition to general ecological understanding, some training in riverine invertebrate taxonomy and ecology is necessary. At the least, the trainee should be able to identify invertebrates to family level, as required in the SASS, and should be able to categorise families by their general habitat requirements and flow dependencies. This level of skill is adequate in the training stage, when the trainee can rely on the supervision of an experienced specialist. Once training is complete, however, the trainee should have a detailed understanding of the BBM process, and the ability and confidence to use judgement in recommending flow requirements. Trainees and specialists alike should be able to recognise which aspects of the invertebrate communities are affected by flow, and which by other processes.

In summary, the minimum qualifications for BBM invertebrate specialists who can operate on their own are:

- a degree in the biological sciences, with some component of ecology, and preferably of river ecology;
- a basic knowledge of riverine invertebrate taxonomy and life histories, and at least the ability to identify invertebrates to family level;
- the ability to recognise and classify different riverine habitats;
- knowledge and experience in sampling methods for aquatic invertebrates;
- some knowledge of the processes and significance of hydrology, hydraulics, water chemistry and geomorphology for riverine invertebrates;
- participation in at least two BBM studies under the supervision of an experienced specialist.

An important safeguard in the process is always to have an experienced river ecologist as the coordinator of a project and as the facilitator at the workshop. This is designed to reduce the likelihood of unrealistic recommendations and motivations being made.

17.10 POTENTIAL PITFALLS

There is no ‘right answer’ in the assessment of flow requirements for a river. In the final analysis, any perturbation of the natural flow regime will have some effects, and the extent of acceptable exploitation of natural water resources will always be a value judgement. On a smaller scale, assessment of a modified flow regime that will maintain a particular invertebrate community in the long term also carries a large measure of subjectivity.

In order for EFAs to be scientifically defensible, they need to have the following characteristics:

- consistency of application and results;
- methods that can be used for any river;
- a high level of objectivity and accuracy.

The BBM represents a major step towards achieving such EFAs. Within the various specialist components of the methodology, including the aquatic invertebrates, there is considerable room for subjective judgement, and any developments that increase the objectivity of the processes used by the specialists will enhance the consistency of results between rivers. With the increasing need to train more specialists, a priority is to develop within-discipline repeatable and transferable methods for use in the BBM, and so to reduce the present reliance on the experience and judgement of a few skilled specialists.

17.11 FURTHER DEVELOPMENTS

The rigorous development of models and indices that can be applied consistently will help to overcome some of the pitfalls described in Section 17.10. Hydrological and hydraulic modelling are highly developed in comparison to ecological modelling, and are used effectively in the BBM. All models are only as accurate as their input data, and ecological models have to cater for large numbers of variables, of which flow and hydraulics are only two. The scope for accurately depicting the complex functioning of a river ecosystem through modelling is therefore narrow. An approach that may be useful in applications of the BBM, but with the link not yet developed, is to use rule-based models. These are designed to apply the expertise of specialists consistently. An index-based method such as SASS4 has many uses, but it is not designed to provide information on flow-linked distribution patterns. Plans are in place to expand the potential of the SASS4 Method, so that SASS4 scores can be produced that indicate the flow conditions that invertebrate families are typically found in.

Another useful development is the growth of studies to ascertain flow conditions that different invertebrate species perceive as different in terms of stress levels. If it is possible to characterise stress levels consistently, then the transferability and repeatability of results will be improved. The present suggestion is that, for any one species, stress-flow relationships can be measured, and therefore daily hydrological time series can be directly converted to stress time series. These, in turn, can be converted to stress profiles for different flow regimes, describing the levels and frequency of stress for a species as water is removed from a river. Such research is in the early stages, but the concepts have great potential to overcome the problems described above.

17.12 MONITORING

Monitoring of invertebrates after an application of the BBM should be done in two phases. Firstly, if this has not already been adequately done, and assuming that some water-resource development is planned, a baseline survey should be completed. The objective of this is to characterise invertebrate communities and environments before the implementation of the development or of the EFR release. Secondly, after the development is complete and the EFR releases have begun, long-term monitoring should be done to ensure that the objectives set at the BBM Workshop are being met.

The monitoring programme should be practical, with components that can be implemented using available expertise and other resources. For the baseline monitoring, initial "Thresholds of Potential Concern" (TPCs) (*sensu* Rogers & Bestbier 1997) should be set. These TPCs represent conditions at which some management action should be taken, before a critical threshold is reached. For instance, in terms of the invertebrates, the TPC could be a SASS4 value below which samples should not drop more than twice in succession. One aim of the baseline monitoring programme would be to use the SASS scores from the collected samples to set this TPC. In addition to the designated SASS threshold, it might also be possible, as an additional TPC, to identify sensitive taxa that should not be absent from samples.

A typical baseline monitoring programme for invertebrates would involve participation of an experienced specialist in its design and implementation, and a monitoring trainee to take over the programme in the long term. The following tasks would be required:

- an initial planning meeting;
- three surveys of invertebrates at all BBM sites, in order to characterise communities in different seasons**;**
- a workshop to set TPCs.

Comprehensive baseline monitoring of this nature, for three pre-development surveys at four sites on a river section of 200 km, would require roughly 36 specialist days and 50 trainee days.

Long-term monitoring, which could be undertaken within the standard monitoring operations of the national River Health Programme, should consist of low intensity sampling to compare conditions with the TPCs and, if necessary, to refine the TPCs.

The following tasks are recommended:

- a SASS4 sample from each habitat at each BBM site, once a year during the low flow season, with associated habitat analysis (e.g. according to McMillan 1998);
- standard SASS4 analysis of the samples, and a more detailed examination of any sensitive species for which TPCs may have been identified;

- once every five years, a complete analysis of invertebrates, to species level where possible, and comparison with pre-development baseline species lists.

The invertebrate sampling and analysis should be coordinated with monitoring of the other ecosystem components, in order to identify any trajectories of change and their causes. If any TPCs are exceeded, there should be moves from management to evaluate the nature and causes of the change, and to decide on remedial actions if necessary.

17.13 CONCLUSIONS

As invertebrates are so diverse, ubiquitous, easily sampled and responsive, they constitute the most useful indicators of conditions in a river, and should be at the core of the BBM process and subsequent monitoring programmes. If costs and resources are scarce, as they often are, available resources can most usefully be directed towards the invertebrate component of the ecosystem, in the expectation of optimum returns for costs incurred. As the River Health Programme of biological monitoring expands nationally, the database on invertebrates is becoming more widespread and useful, since invertebrates also form the core component of this programme.

18. FISH

Neels Kleynhans and Johan Engelbrecht

18.1 FISH IN RIVER STRUCTURE, FUNCTIONING AND MANAGEMENT

As fish assemblages often include a range of species that represent a variety of trophic (feeding) types (i.e. omnivores, herbivores, insectivores, piscivores), they reflect the integrated effects of environmental changes. Their presence, therefore, can also be used to infer the presence of other aquatic organisms, since the adults occupy the top of the food chain in most aquatic systems. They also pass through most trophic levels above the primary producer stage during their development from larvae to adults. Fish assemblage structure can thus be regarded as reflecting the integrated environmental health of a river (Karr *et al.*, 1986).

If the species richness in a river is sufficiently high and the structure of the fish assemblage is sufficiently diverse, then knowledge of the environmental conditions needed by fish to complete their life cycles can contribute greatly to an understanding of the functioning of that river. It can also guide specification of the flows necessary to meet their needs, and be useful in the monitoring and management of those flows. In general, it is also often surmised that if management of flows for fish maintenance is successful, then flow requirements for aquatic invertebrates will also be satisfied. This is because of the larger scale of fish habitat.

The approach described in this chapter for including fish in EFAs is mostly generic, as this makes it possible to apply to rivers across the country. As quantitative ecological information on many of the indigenous fish species of South Africa is limited, considerable use is made of expert knowledge and professional opinion. It is, thus, highly recommended that ecologists who apply this approach should know the river and its fish at least reasonably well.

18.2 FISH STUDIES IN THE BUILDING BLOCK METHODOLOGY

Members of the public, and resource managers, are usually more aware of and concerned with the existence and wellbeing of fish than with other forms of aquatic life. Consequently, aspects such as the ecological requirements for fish maintenance, the use of fish as indicators of the ecological importance and sensitivity of a river, and fish as sentinels of ecological integrity, can often be used to explain the reasoning behind the recommendation of particular environmental flows. As a result of their relative longevity and mobility, fish are also good indicators of long-term (several years) effects on the riverine ecosystem and of broad habitat conditions. Thus, monitoring the presence and distribution of fish is often regarded as an essential tool in the determination of whether or not the goals of management have been achieved (Karr *et al.*, 1986).

The primary subject of this chapter is the use of fish as an ecosystem component in an EFR determination using the BBM. However, the topic of fish as indicators of biological integrity and of ecological importance and sensitivity, also is discussed briefly.

18.2.1 Flow requirements

In the BBM, information on the ecological, flow-related requirements of various life history stages of different fish species is used to guide recommendations for required future flows in the river. The hydraulic habitats required by the different fish species or their life history stages are usually defined by baseflow conditions, whilst a series of life stage cues or habitat requirements may rely on high flow events. For example, some fish species need permanent flow in a specific habitat during all their life stages, while others need specific high flow events during migration, spawning or larval stages. High flows may be needed to initiate the development of gonads, and to clean spawning beds and nursery areas. The following examples serve to illustrate how fish can be used in the estimation of EFRs.

Example 1

Fish species with specific habitat and feeding requirements, and/or requirements associated with riffles, are likely to be most dependent on perennial flow. This dependence can often be related to their water quality requirements, such as a specific range of oxygen concentrations and water temperatures. Some riffle-dwelling species, such as the majority of *Chiloglanis* spp., are dependent on perennial flow during all stages of their life cycle (Gaigher 1969), while other riffle dwellers, or at least certain of their life stages, can survive in pools during periods of low or even no flow. These differing requirements provide important pointers as to the magnitude, distribution and constancy of low flows needed during the dry season.

Example 2

For breeding and nursery requirements, many fish species are dependent on sand or gravel beds, or on shallow, slow-flowing backwaters with inundated marginal vegetation. The temperature and volume of water in such areas are major factors contributing towards successful spawning and recruitment. Gonad development and maturation followed by successful spawning may, however, also require a combination of stimuli at different times. These could include increased current velocity, specific water quality changes (e.g. changes in EC, or an influx of organic substances from the catchment following rain), maintenance of specific water temperatures over a period of time, changes in barometric pressure, and releases of pheromones (Lowe-McConnell 1975). However, fish recruitment does not depend only on successful spawning, but also on the maintenance of favourable conditions during development of the embryos and larvae. The larval stages of several fish favour nursery areas that are rich with zooplankton, and characterised by shallow, warm water with low velocities. The times and durations for which these stimuli and areas are available are important considerations when setting flow requirements for periods that may include fish breeding and recruitment activities.

Example 3

Several truly catadromous fish species occur in a number of South African rivers. These include the eels (i.e. *Anguilla mossambica, A. marmorata* and *A. bengalensis labiata*) and the freshwater mullet (*Myxus capensis*) (Skelton 1993). It is of critical importance for the survival of these species that the adults are able to migrate downstream to the sea to spawn, and that the juveniles can migrate upstream again to their freshwater feeding and maturation areas. Eel larvae, for instance, are carried from their spawning grounds in the Indian Ocean, southwards via the Mozambique and Agulhas currents, beyond the coast of southern Africa. The juveniles, or glass eels, enter South African rivers during January and February each year and migrate upstream. It is extremely important that freshwater cues reach the ocean during this period to attract these juveniles into the rivers.

It is surmised that by meeting flow-related habitat requirements in rivers for the abovementioned sensitive species or life history stages, flow requirements for the majority of associated primary and secondary freshwater fish species will also be satisfied.

18.2.2 Biological integrity

Assessment of biological integrity of rivers is often based on indices that make use of attributes of fish assemblages, such as species richness, assemblage composition, trophic composition, habitat guilds and health and condition. Of these, the Index of Biological Integrity (IBI; Karr 1981) and its variations are commonly used (Hughes & Oberdorff 1999; Kleynhans 1999b). This kind of assessment, in combination with the assessment of other groups of biota, contributes to an understanding of the current ecological state of the river. It also aids formulation of an attainable desired ecological state or EMC (Chapter 11).

18.2.3 Ecological importance and sensitivity

Fish data are also useful when ascertaining the ecological importance and sensitivity of rivers (Chapter 10; Kleynhans 1999c), for the following reasons:

- the conservation status of most fish species has been determined (Skelton 1987);
- the general ecological requirements of most species are relatively well known;
- their distribution patterns in many rivers are on record.

18.3 SEQUENCE OF ACTIVITIES

18.3.1 Assessment of available information

The first activity is the assessment of available information:

- Identify the river or river sections of concern.
- Locate available fish information for the river, including that from Provincial Nature Conservation organisations, museums and published accounts.
- Identify the geomorphological zones in the study area (Chapters 8 & 14), and allocate the available information on fish distributions to the relevant zone(s).
- Assess the information on fish distributions, and decide if each zone is adequately represented and thus, if the information is sufficient for BBM purposes. Points to consider would be: date of last survey and its level of detail; the number of sites; and the representativeness of the fish listed.
- If the fish information is inadequate, plan and conduct a fish survey (Section 18.3.2), and then collate all the information (Section 18.3.3).
- If fish information is adequate, collate all information (Section 18.3.3). However, it is highly recommended that even when fish information is abundant and was recently collected, a fish survey of the BBM sites should still be conducted (Section 18.3.2).

18.3.2 Planning and conducting a fish survey

Note that although fish surveys may be required to obtain specific information on the fish species of the study area, this second activity does not constitute a research programme *per se*.

Planning the survey

- Sites to include in the fish survey are tentatively identified. This is done using information on the geomorphological zonation of the river, the location of identified BBM sites (Chapter 7), topocadastral maps and the video of the low-altitude helicopter survey (Chapter 8), as well as whatever historical data are available. Suitable sites are those that are reasonably conducive to efficient sampling of the various habitat types present. However, river sections known to be impacted by anthropogenic activities should be taken into account and, if possible, sites located upstream and downstream of such impacted sections. These will provide information on the PES of the river, and influence which EMC is decided upon for the river or river zone. The BBM sites should be regarded as the primary sites for collecting fish data, and if other sites are chosen they should be located near the BBM sites, so they can compensate for any lack of fish data from the primary sites. In total, the fish data should be seen as representing a particular length of river, and not any one point or site.
- Decide whether or not a once-off survey will be sufficient, or whether seasonal information is required. This decision can have important implications for budgets. The decision should be based on when the last survey was done, and the level of knowledge on flow-related requirements of different life stages of the species present.
- It is not possible to prescribe the number of fish survey sites that should be included per river zone, as this will be influenced by factors such as the lengths of the zones, the locations of existing impacts and accessibility. Experience should be relied upon in these situations. However, a possible minimum number of sites is one BBM site per zone, as well as one site upstream and one downstream of each of these for additional fish surveys.

Conducting the survey

In this section, guidelines are provided as to the kind of information required for BBM purposes. It is not intended to provide an overview of sampling methods. Generally, fish surveys conducted for BBM purposes will not be aimed at providing a comprehensive assessment of the biological integrity of a river, but rather at providing information on flow-related aspects of fish species and their habitats.

- Except where seasonal information on the flow requirements of fish species is required, it is strongly recommended that fish surveys be conducted during the dry season wherever possible.
- In the field, the physical habitats at sites should be assessed, to ascertain if they are representative of the zone and if sampling is possible. If either of these criteria is not met, then alternative sites should be sought.
- During sampling, the species and life history stage of each fish caught should be recorded, together with details of its physical habitat and cover. The approach of Oswood & Barber (1982) can be used to categorise flow (velocity)-depth classes as listed below.
    - Slow (<0.3 m s^{-1}) and shallow (<0.5 m); includes shallow pools and backwaters.
    - Slow (<0.3 m s^{-1}) and deep (>0.5 m); includes deep pools and backwaters.
    - Fast (>0.3 m s^{-1}) and shallow (<0.3 m); includes shallow runs, rapids and riffles.
    - Fast (>0.3 m s^{-1}) and deep (>0.3 m); includes deep runs, rapids and riffles.

- Cover can be categorised as follows.
    - Overhanging vegetation: thick vegetation overhanging water by approximately 0.3 m and not more than 0.1 m above the water surface (Wang *et al.,* 1996). This definition includes marginal vegetation.
    - Undercut banks and root wads: banks overhanging water by approximately 0.3 m and not more than 0.1 m above the water surface (Wang *et al.,* 1996).
    - Stream substratum: various substratum components that provide cover for fish, such as fractured bedrock, boulders, cobbles, gravel, sand, fine sediments and woody debris ("snags").
    - Aquatic macrophytes: submerged and emergent water plants.

18.3.3 Collation and analysis of data on fish distributions and related ecological conditions

The ecological information required for this third and final activity can be found in works such as Crass (1964), Jubb (1967), Gaigher (1969), Pienaar (1978), Kleynhans (1984), Bell-Cross & Minshull (1988), Skelton (1993), Russell (1998) and Weeks *et al.* (1996). If there are few recorded data, it is also advisable to obtain inputs from local fish experts.

Flow and habitat requirements of fish

The physical habitats for fish that are found in each identified geomorphological zone are described in general terms. This information can be tabulated, for instance, in terms of the presence and relative abundance of riffles, rapids, pools, backwaters and runs. For each geomorphological zone, ecological information on each fish species present can be collated in the following way.

- Tabulate habitat and flow requirements, including depth and velocity requirements. Include available information on the habitats typical for the different life history stages (i.e. ovum, larva, juvenile, subadult, adult). Provide quantitative details if possible, or follow a semi-quantitative or qualitative approach. The approach of Oswood & Barber (1982) can be used to categorise velocity-depth classes (Section 18.3.2).
- Tabulate characteristic cover for all life history stages, in terms of such features as substratum, marginal and overhanging vegetation, undercut banks and root wads. Provide quantitative details if possible, or follow a semi-quantitative or qualitative approach (Section 18.3.2).
- Identify fish species that are indicative of, representative of, and/or sensitive to, particular physical and chemical conditions. If possible, identify species and life history stages that are characteristic of slow-shallow, slow-deep, fast-shallow and fast-deep flow-depth classes and particular cover types.
- Collate information on breeding requirements and characteristics, including time and length of breeding season, fecundity, breeding stimuli, migration and spawning habitat. Indicate any links with the flow regime.
- Categorise and tabulate the tolerances of species towards different kinds of river flow, as follows:
    - tolerant: species with no particular flow requirement during any life history stage - such species can survive and reproduce in the absence of flow;
    - moderately tolerant: species that require flow during particular life history stages such as breeding and migration;
    - intolerant: species that have a requirement for flowing water during all life history stages.

- Categorise and tabulate the tolerance of species towards changes in water quality, as follows:
    - tolerant: species that are relatively hardy with regard to changes in water quality;
    - moderately tolerant: species that can endure some changes in water quality, but some life history stages may be sensitive to changes;
    - intolerant: species that can endure only very limited changes in water quality, because all life history stages are sensitive to changes.
- Categorise and tabulate species with respect to their habitat and cover preferences, as follows:
    - tolerant: species with no particular habitat or cover preference;
    - moderately tolerant: species with a preference for certain habitat and cover types during some life history stages;
    - intolerant: species with specific habitat and cover requirements during all life history stages.
- Categorise and tabulate species in respect of their food preference attributes, as follows:
    - tolerant: species with no particular food preferences;
    - moderately tolerant: species with a moderately high degree of food preferences;
    - intolerant: species with a high degree of food preferences.

Biological integrity

The use of fish to assess biological integrity in the BBM, is usually less detailed than for biomonitoring surveys in the River Health Programme (Roux 1997; Kleynhans 1999b). Ecological information on the fish assemblage in different sections of the river is used to gain a general estimate of the river's biological integrity. This information complements that of other biological assessments, such as those of aquatic invertebrates (Chapter 17) and habitat integrity (Chapter 8). Where comprehensive sampling of fish assemblages has been carried out, the river can be categorised in terms of its biological integrity using the approach of Kleynhans (1999b) or the IBI methodology (Karr *et al.,* 1986). If this has not been done, an alternative approach could be based on a comparison of the expected fish assemblage under minimally impaired conditions, and that actually present. This approach is similar to the habitat integrity categorisation (Chapter 8 & Table 18.1). Specific requirements for the fish assemblage to be categorised as falling within a particular class should be formulated based on fish species present in a zone, at a site and in the habitats sampled at a site.

- The fish species expected to be present in a particular zone and each of their habitats are used to describe the Reference Condition.
- The fish species actually caught within a specific site and habitat are compared with the Reference Condition.
- Based on an analysis of the expected versus observed situation, the fish assemblage at the site is categorised according to the generic criteria in Table 18.1. Information on the levels of intolerance (where intolerant species are sensitive to environmental disturbance and associated changes from natural condition), and habitat and trophic characteristics of species is taken into account in this categorisation. The reasons for the resulting categorisation should be consistent and explicable, even if they are not based on quantitative data.

Table 18.1 Generic classes for assessment of biotic integrity, using fish (from Kleynhans 1999b).

CLASS	EXPECTED FISH ASSEMBLAGE
A	Unmodified, or close to that occurring in natural conditions.
B	Largely natural with few modifications. A mild change in assemblage characteristics may have taken place, but species richness and the presence of intolerant species indicate that this has been very slight.
C	Moderately modified from natural. Species richness and number of intolerant species lower than for natural conditions. Some impairment of fish health may be evident at the lower end of this scale.
D	Largely modified from natural. Species richness lower than for natural, and intolerant or moderately intolerant species absent or reduced in abundance. Impairment of fish health may become more evident at the lower end of this class.
E	Seriously modified from natural. Species richness strikingly lower than for natural conditions, and intolerant and moderately intolerant species mostly absent. Impairment of river health is very evident.
F	Critically modified from natural. Species richness extremely low, and intolerant and moderately intolerant species absent. Only tolerant species present, with a complete loss of species at the lower end of the class. Impairment of river health is very evident.

Ecological importance and sensitivity based on fish

Data on the ecological integrity of a river, that is, its PES, and on the distribution of fish can contribute to an assessment of the ecological importance of a river (Chapter 10). In addition, the available ecological information on fish can be used to assess the sensitivity of a river to various forms of environmental disturbance. The following tasks should be undertaken for the assessment of the ecological importance and sensitivity of the river zones being investigated.

- Assess the conservation status of fish species, based on the South African Red Data Book of Fish (Skelton 1987). This information is provided at the national scale. In most cases, the conservation status of species at a provincial or local scale has not been formally assessed, but can usually be obtained from local specialists.
- Note the presence of unique species or species that are otherwise important from a conservation perspective, such as those that are endemic or have isolated or genetically unique populations. If possible, indicate the relevance of this at national, provincial and local scales.
- Ascertain the species richness of fish in the river, and their abundances if possible. Compare the values for different zones of the river, and for different rivers.
- Use the information on the tolerance of fish species to various environmental conditions, to provide an indication of the sensitivity of the river to various forms of disturbance. For instance, the presence of a large number of species with a requirement for flowing water during all life history stages, is an immediate indication of the high sensitivity of the river or river zone to flow modifications.

18.4 MINIMUM AND IDEAL DATA SETS

Minimum and ideal data sets are two extremes along a continuum, and most often, the actual data set will lie somewhere in between. The decision as to whether a minimum data set will suffice, or whether a more comprehensive data set is necessary, will depend on factors such as the current and desired ecological integrity of the river and its ecological importance and sensitivity (Chapters 8, 10 & 11).

A minimum data set would consist of recent historical records of fish species occurring in the river, and a fundamental understanding of the flow-related habitat requirements of the most sensitive species or life history stages. If no or insufficient historical data are available, at least one fish survey should be conducted in each designated geomorphological zone in the study area. This survey should be conducted at the selected BBM sites towards the end of the low flow season, as this usually represents the most critical period for fish survival.

An ideal data set would consist of a complete, representative, historical and current record of all fish species in the study area, and of the flow-related requirements of all their life history stages, in all geomorphological zones being investigated. It would be ideal to also have such detailed fish information for all the designated BBM sites. However, such data sets are rarely available and may take years to compile.

When defining flow requirements for fish, it is crucial to know the range and areal extent of different physical conditions available at each BBM site over a range of known discharges. Such information should be drawn from wet and dry seasons, from the most important species and from all sites. This will enable identification of important spawning and nursery areas or other critical microhabitats during the high flow season, as well as potential threats to the fish posed by low flow conditions. It must be remembered that BBM sites are often a compromise between sites that would well illustrate the relationship between fish and the flow regime, and those that allow reasonably accurate modelling of local hydraulics (Chapter 13). Consequently, it may be necessary to supplement data from BBM sites with ecological information on fish species from other sites.

18.5 STARTER DOCUMENTATION FOR THE WORKSHOP

The purpose of the chapter for the BBM Workshop starter document is to enable the workshop participants to form a perception of the relationship between fish and river flow. It also provides data that can be used in estimations of the ecological importance, sensitivity and biological integrity of the river in the study area. The document should be concise, providing only information relevant to the investigation. It should consist largely of tables of the collated information and short discussions where appropriate. The following topics should be included.

- A list of species expected to be present in each geomorphological zone, indicating their conservation status on a national, provincial and local scale, and any unique or otherwise important species.
- Habitat suitability data for each fish species, indicating preferences and tolerances for different hydraulic and other physical and chemical conditions.
- A list of species expected to be present, and those actually present at each BBM site. A categorisation of the biological integrity of each site, and in a generalised way for each zone, using the classes in Table 18.1. Where possible, detailed information should be provided on sites and an attempt made to relate fish requirements to hydraulic cross-sections, if this information is available prior to the workshop.

- Conclusions on flow and other habitat requirements for all or selected fish species, indicating differences for each life history stage. Sensitive and indicator species or life stages should be identified, that would be useful for representing the ecosystem for flow-related purposes.
- Conclusions and explanations of the current biological integrity class of the river, based on data on fish assemblages.

18.6 ROLES AND RESPONSIBILITIES AT THE WORKSHOP

At the BBM Workshop, a presentation is given of the current biological integrity and ecological importance of the river from the perspective of the fish biologist, and of the flow-related requirements for fish in each designated zone. On the understanding that the participants have read the starter document, only the main points are summarised, and the emphasis is on the flow-related environment of fish. Where more detail is required in later group discussions, the authors of the fish report explain and advise workshop participants on the flow-related habitat requirements for different life history stages of all fish species of interest.

18.7 ROLES AND RESPONSIBILITIES AFTER THE WORKSHOP

The fish report for the workshop is often compiled without access to the reports written by the other specialists in the BBM team. Relevant information, such as the geomorphological classification of zones and the water quality assessment, may not be available until the workshop, and should be captured and incorporated into the final version of the report. Additionally, other fish experts may participate in the workshop, and their insights and professional knowledge may contribute significantly to the understanding of flow requirements for fish. Where appropriate, this knowledge should also be included in the final version of the report.

18.8 EXAMPLE OF TERMS OF REFERENCE

18.8.1 Pre-workshop

Depending on the extent and aims of the investigation, the study should cover the following aspects.

- A review of all geographical distribution records for fish in the study area. Where such information is sparse, reference should also be made to similar stretches of comparable rivers.
- A survey of fish species in all habitats at each BBM site, to provide data on their distributions and abundances. If the BBM sites are not representative of all fish habitats, additional nearby sites should also be sampled.
- Provision of the conservation status of all fish species actually found during the survey(s), as well as of those expected to be present based on historical information.
- Based on the current survey and historic information, provision of an approximate estimate of the biological integrity of the river and geomorphological zones of the river based on fish assemblages.

- Using all available literature and the results of the current survey, collation of data on the flow-related habitat requirements of all life history stages of all fish species present in the river.

18.8.2 At the workshop

- Contribute towards the specification of the desired EMC, with reference to fish species.
- Advise workshop participants on the flow-related habitat requirements of fish species.
- Provide an assessment and explanation of the current biological integrity of the river, based on fish assemblages.

18.8.3 Post-workshop

- Complete the final version of the fish chapter for the workshop starter document.
- Review the workshop report in terms of motivations for flows required by fish.
- Define ecological endpoints in terms of the species expected to be present and their expected abundances under the desired EMC. These defined endpoints will form the basis of future monitoring programmes.

18.9 MINIMUM AND OPTIMUM SPECIALIST TRAINING

If a fish survey is not required or if a very limited one will suffice, the person responsible for the analysis and interpretation of data and report writing should have professional training and experience in fish ecology. This person should preferably have experience in the assessment and interpretation of information and data for applications of the BBM. If this is not possible, someone with this experience should advise the person responsible.

If a fish survey is required, it should be conducted by a trained and experienced team under the supervision of the fish specialist who has been appointed to the BBM team. Ideally, this ecologist should have extensive professional training and experience in this field, have been involved in previous BBM applications, and should know the river and its fish species well.

18.10 POTENTIAL PITFALLS

Although fish can provide valuable information for use in EFAs, there may be some problems. For instance, the species richness of fish in several South African rivers is very low. This is true for whole river systems in several different geographical regions of the country, and for the upper reaches of most rivers. Consequently, the amount of flow-related information gained from such situations may be very limited. It may be wise, therefore, to place greater emphasis on other ecosystem components such as invertebrates, if these occur under a wide range of hydraulic conditions and flow-related data are available for them. In the same context, many of South Africa’s fish species are adapted to naturally diverse and environmentally harsh conditions. As such, they may not always be good indicators of flow-related requirements, even if species richness is comparatively high. This is partly due to difficulties in defining the requirements of different life stages, and also because they can exist in a wide range of conditions.

Another potential problem relates to the limited amount of data on the flow-related preferences, particularly of early life history stages, of many South African fish species. Often, deductions regarding ecology have to be made based on personal experience of related species. There are inherent dangers associated with using such an information base, and a precautionary approach should be followed in the specification of flow requirements for such species.

18.11 FURTHER DEVELOPMENTS

Specification of environmental flows for South African fish species is predominately based on expert knowledge and experience. These specifications must eventually be based on more formal and scientifically founded quantification of the flow-related needs of fish. A national target would be to have HSI curves (Bovee 1982) for all life history stages of all species. However, BBM contracts do not presently offer much potential for further development of such data and understanding. Thus, although much information is obtained during general fish surveys and biomonitoring studies, specific research is required on the ecology and life history strategies of various fish species. This will allow more quantified and confident recommendations on flow requirements.

18.12 MONITORING

Monitoring of fish to determine if the EFR is being met and the specified EMC attained, goes beyond the BBM and is a separate exercise. However, one of the products of the BBM Workshop should be the specification of ecological endpoints for fish assemblages in each river zone. These endpoints will indicate if the EMC is being attained from the perspective of the fish biologist. The development of a monitoring programme should be based on these specifications, and an expert system or decision support system should be developed to assess the results of fish monitoring exercises (Kleynhans 1999b).

Provision should be made in such a system for feedback loops that allow flow specifications to be refined, based on the accumulated results of long-term monitoring of the fish assemblages. As a result of the scarcity of quantified ecological information on fish and other aquatic species in South Africa, refinement of the EFR and other management activities through monitoring programmes is vital.

18.13 CONCLUSIONS

Fish species potentially can provide a very important perspective on the flow requirements of riverine ecosystems, due to their diversity of life history strategies and the variety of habitats utilised during these stages. Currently, the use of fish in EFAs is often hampered by a lack of quantified ecological information. Species for which some ecological information is available thus often are used as surrogates or indicators of general flow-related requirements. Additionally, even for many well-studied species, the flow-related requirements of all life history stages are not adequately known or taken into account. To better utilise fish as a component in the BBM, there is an urgent requirement for a steady growth in quantified ecological information for South African fish species.

19. GROUNDWATER

Roger Parsons

19.1 GROUNDWATER AND THE FUNCTIONING OF RIVERS

Groundwater plays a number of key roles in the functioning of aquatic systems, including:

- contributing to rivers and wetlands as baseflow;
- supplying water to vegetation in the near surface zone;
- sustaining pools and riffles during low flow and dry periods;
- storing water which then is available long after recharge has taken place.

It is beyond the scope of this document to describe these roles, but for further details see Lerner (1996); Scott & Le Maitre (1998); Hatton & Evans (1998); DWAF (1999d); Gardner (1999); Petts *et al*. (1999); and Toth (1999). Figure 19.1 illustrates the integrative function groundwater plays in aquatic ecosystems, indicating its links to a range of landscape features. To facilitate a systems approach to understanding the importance of groundwater as part of South Africa’s water resources, DWAF (1999d) introduced the concept of geohydrological regions. A geohydrological region is defined as an area within which the geohydrological characteristics are similar, resulting in the area fulfilling a unique and specific role in the hydrological system. These regions are used when setting the groundwater component of the Reserve (DWAF 1999d). However, they are also particularly useful for illustrating to non-groundwater specialists the role groundwater plays in sustaining rivers.

The groundwater component of the hydrological cycle cannot be considered in isolation, but should recognise the strong interrelationship between quantity and quality, surface water and groundwater, the saturated and the unsaturated zone, and with the catchment of which they are part (Braune 1997). Further, resource protection is fundamentally related to use, development, conservation, management and control. Integrated catchment management hence must form the cornerstone of quantifying and managing water resources.

From an ecological perspective, the significance of groundwater is greater for non-perennial than for perennial rivers. Reduced amounts of groundwater might mean lower flows in a perennial river, but could lead to earlier and longer exposure of the bed of non-perennial rivers, and to a water table that could not be reached by riparian vegetation. Also, particularly in non-perennial systems, the volume of groundwater may be less important than its presence during critical dry periods. O'Keefe *et al.* (1998) noted that aquifer storage of water buffers aquatic systems such as rivers against seasonal variation in rainfall, thereby having a major influence on their overall nature. For example, groundwater discharged into pools during low flow periods is probably not measurable as flow, but it may maintain their water levels and thus provide critical refugia for aquatic species. Such situations are typical of seasonal rivers and are of greater relevance during dry months and periods of prolonged drought. Consideration of groundwater levels is thus paramount when considering environmental flows for the maintenance of river-related ecosystems.

Though this chapter focuses on the relationship between groundwater and rivers, many of the principles, concepts and methods also apply to interactions between groundwater, and estuaries and wetlands. These relationships probably vary quite widely and need to be addressed on a case-by-case basis.

19.2 GROUNDWATER STUDIES IN THE BUILDING BLOCK METHODOLOGY

Groundwater is an integral part of the hydrological cycle, as now formally acknowledged in the new National Water Act No. 36 of 1998. It has not played a major role in BBM applications yet, although it was addressed in the Sabie-Sand River System and Mogalakwena River environmental flow studies (Tharme 1997c; Ractliffe 1996; respectively). In response to the new Water Act, however, development of tools to assess the Reserve (Chapter 4; DWAF 1999d; Braune *et al*., 1999) has resulted in greater recognition being given to this component. It is expected that groundwater considerations will take on greater prominence as more Reserve determinations are undertaken.

The primary role of geohydrologists in an application of the BBM is to provide specialist geohydrological input as a member of the multidisciplinary BBM team. Two levels of input are generally required. As aquifers extend across entire catchments (unlike rivers, which are more or less confined to the river channel) an understanding of geohydrological conditions throughout the catchment is required. This understanding is used then to assess geohydrological characteristics and functioning at the local scale, that is, in the immediate area of each BBM site.

Particular activities where geohydrological input is vital include:

- development of a conceptual understanding of prevailing geohydrological conditions, and of the role groundwater plays in supporting river flows and aquatic ecosystems;
- assessment of the role and control of geological and geohydrological parameters on ecosystem characteristics such as baseflow, subsurface flow, surface water quality and channel morphology;
- identification of unique or characteristic systems, based on their geological or geohydrological considerations (ecoregions);
- assessment of groundwater contribution to baseflow;
- assessment of geohydrological controls and functions at BBM sites;
- description of groundwater management and protection required to ensure continued functioning of the river system;
- assessment of the geohydrological influence on operational management of proposed dams.

19.3 SEQUENCE OF ACTIVITIES

A number of actions are required to ensure that the groundwater component is adequately addressed. These generally relate to the three phases of an assessment using the BBM: the pre-workshop, workshop and post-workshop phases.

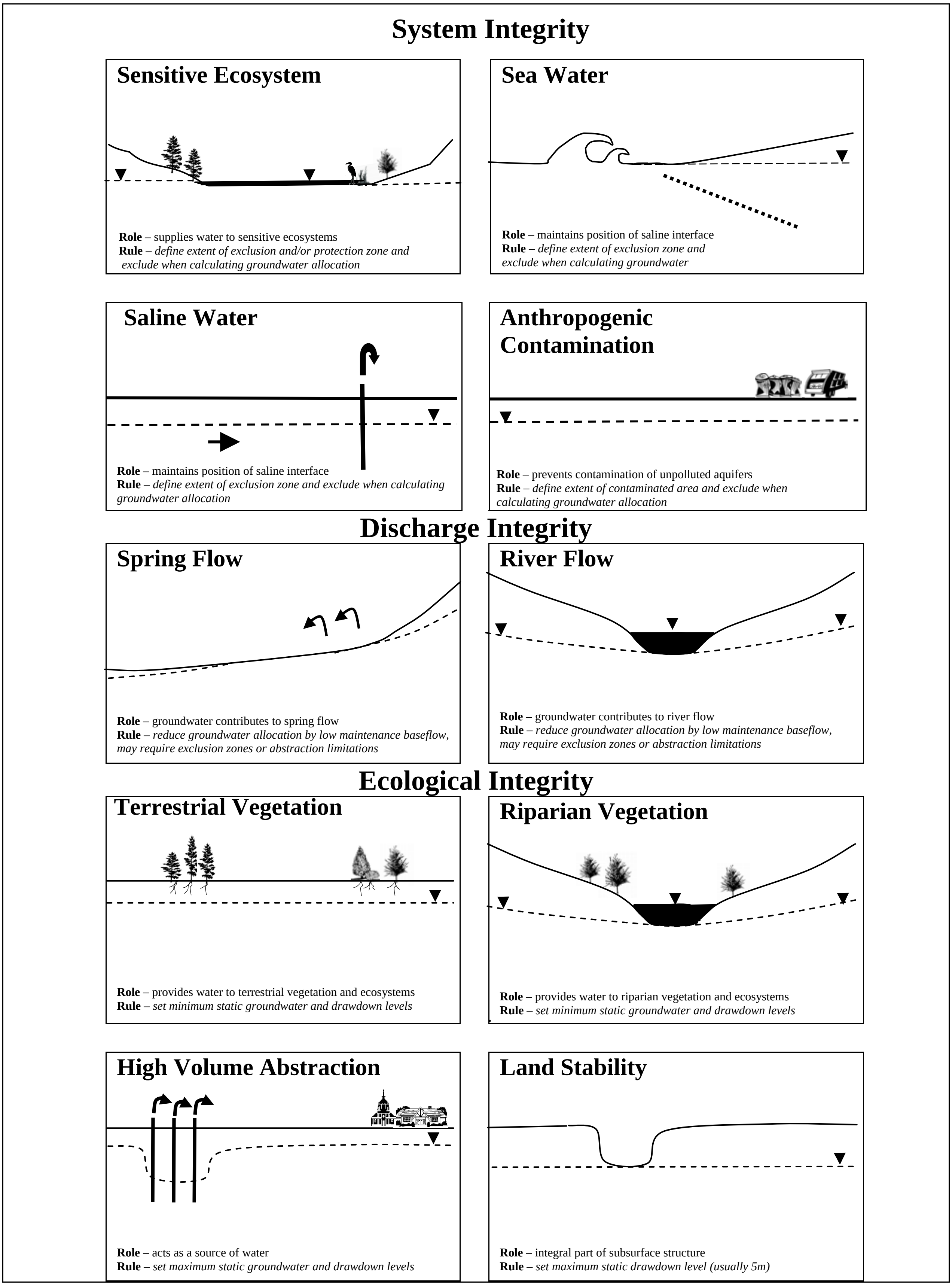
19.3.1 Pre-workshop

Data and information are gathered to provide meaningful geohydrological input into the BBM process. The intensity of this stage is generally controlled by the perceived role of groundwater in the river’s functioning, the level of confidence required and the available budget. The following activities are completed:

- collection of all available relevant information (including existing data sets, reports and maps);
- preliminary site visit, including a hydrocensus, which is a survey of local groundwater use and borehole information;
- analysis of available data;
- fieldwork (if required);
- analysis of data;
- preparation of a geohydrological report for the starter document for the BBM Workshop.

Development of a sound conceptual understanding of prevailing conditions is a key outcome of this task. Discussion with geohydrologists who have worked in the area previously, is an effective and invaluable help in developing the required conceptual model.

The report for the starter document should be clear and concise, allowing readers with a limited geohydrological understanding and limited time, to digest and understand all relevant information.



Sensitive Ecosystem

Role – supplies water to sensitive ecosystems
Rule – *define extent of exclusion and/or protection zone and exclude when calculating groundwater allocation*

Sea Water

Role – maintains position of saline interface
Rule – *define extent of exclusion zone and exclude when calculating groundwater*

Saline Water

Role – maintains position of saline interface
Rule – *define extent of exclusion zone and exclude when calculating groundwater allocation*

Anthropogenic Contamination

Role – prevents contamination of unpolluted aquifers
Rule – *define extent of contaminated area and exclude when calculating groundwater allocation*

Spring Flow

Role – groundwater contributes to spring flow
Rule – *reduce groundwater allocation by low maintenance baseflow, may require exclusion zones or abstraction limitations*

River Flow

Role – groundwater contributes to river flow
Rule – *reduce groundwater allocation by low maintenance baseflow, may require exclusion zones or abstraction limitations*

Terrestrial Vegetation

Role – provides water to terrestrial vegetation and ecosystems
Rule – *set minimum static groundwater and drawdown levels*

Riparian Vegetation

Role – provides water to riparian vegetation and ecosystems
Rule – *set minimum static groundwater and drawdown levels*

High Volume Abstraction

Role – acts as a source of water
Rule – *set maximum static groundwater and drawdown levels*

Land Stability

Role – integral part of subsurface structure
Rule – *set maximum static drawdown level (usually 5m)*

Figure 19.1 The integrating role of geohydrological systems in the landscape, and suggested rules regarding restrictions on abstraction.

Additional data and information can be presented as appendices and during the workshop, or included in the post-workshop documentation.

19.3.2 At the workshop

A brief presentation of geohydrological conditions is given at the start of the BBM Workshop, to give delegates an overview of the role groundwater plays in the functioning of the study river and surrounding area. During the workshop, as flow regimes to achieve the required river condition are discussed, the attending geohydrologist contributes any pertinent information.

In many instances, insufficient data are available to answer questions from the rest of the BBM team, and expert judgement and opinion must be used. In such instances, assumptions need to be fully documented.

19.3.3 Post-workshop

A number of activities are required on completion of the workshop. The chapter on geohydrology for the starter document is updated, based on insights gained during the workshop. Important data gaps identified during the workshop may require additional data collection and analysis.

The importance of monitoring groundwater as part of the EFR monitoring programme (Chapter 22) cannot be overemphasised. In many instances, geohydrological inputs into the process are driven by limited data and expert judgement. The only means of ensuring that the input was valid is to monitor the response of the geohydrological system to natural and anthropogenic influences. Further, as the outcome of the BBM assessment could have significant bearing on environmental sustainability and economic development, ongoing monitoring is critical for assessing the validity of the determined EFR, as well as for improving knowledge and understanding of the role groundwater plays in the functioning of the river.

19.4 MINIMUM AND IDEAL DATA SETS

Geohydrological data collected for BBM assessments are often a function of available budget and time. A balance thus needs to be attained between the role and importance of groundwater in a particular study, the desired level of confidence and the resources allocated.

A large amount of geohydrological information is available with which to develop a conceptual understanding of the geohydrological characteristics and functioning of a system (Table 19.1). The National Groundwater Database (NGDB), national scale geohydrological maps (Vegter 1995; Baron *et al.*, 1998; Parsons & Conrad 1998) and regional scale geohydrological maps currently being produced by DWAF represent important sources of information. These may be supplemented with other readily available information (rainfall data, geological maps, WR90 data), to produce the minimum information required to provide a low confidence geohydrological input into BBM assessments.

Availability of site-specific and monitored geohydrological data lags behind equivalent surface water data. As a means of overcoming this, a hydrocensus is an effective means of collecting site-specific data relatively quickly and at low cost. A two- to three-day visit to the catchment of interest, to interview people using or knowledgeable about groundwater, is usually a minimum requirement. However, the extent of the hydrocensus needs to be governed by the availability of site-specific data (NGDB or reports), the importance of the river system and the importance of groundwater in the functioning of that river.

Site-specific geohydrological investigations usually entail geological mapping, interpretation of aerial photographs and remote sensing information, geophysical surveys, drilling, aquifer testing and sampling. The need to carry out such investigations, and their extent, are driven by project and site-specific considerations. Before embarking on such studies, the objectives and required outputs, and their value to the BBM assessment, need to be addressed critically.

Geohydrological modelling is a useful means of characterising geohydrological conditions and assessing geohydrological response to different scenarios (Chapter 22). Models are very useful predictive tools, but to play a meaningful role in BBM assessments they would have to be:

- based on sufficient site-specific data;
- able to cater for local homogeneity and heterogeneity;
- capable of modelling surface-groundwater interaction;
- properly calibrated and validated.

Though unlikely to become the norm, the ideal data set would consist of sufficient data to develop a properly calibrated and validated groundwater model.

19.5 STARTER DOCUMENTATION FOR THE WORKSHOP

The following is a brief list of what is required in a groundwater report for the workshop starter document:

- locality map showing area of consideration;
- description of underlying geological formations, supported by a geological map and cross-sections;
- description of aquifer properties of the study area, including aquifer type, thickness, transmissivity and storativity;
- data on groundwater level (depth to water, hydraulic gradient, direction of flow) with particular reference to spatial and temporal variation, using a groundwater contour map and time series graphs if possible;
- description of groundwater recharge mechanisms and quantification thereof;
- information on surface-groundwater interactions, and the role groundwater plays in supporting the river;
- analysis of groundwater quality;
- information on known groundwater contamination and, based on land use, potential sources of contamination;
- data on groundwater usage, its importance as a resource and any impacts resulting from such use;
- classification of the aquifer;
- assessment of aquifer vulnerability.

Table 19.1 Types and sources of data used to describe and quantify groundwater functioning.

DATA NEEDED	DATA AND INFORMATION	SOURCE
Geology Lithology • stratigraphy • structure • aquifer types	Geological maps 1:250 000 1:50 000 (if available)	Council of Geoscience
• physiography • catchment boundaries • drainage • slope and topography • land use • other	Topographical maps 1:250 000 1:50 000 (if needed)	Directorate of Surveys and Land Information
Geology Physiography	Remote sensing data • satellite images • aerial photographs	Satellite Applications Centre; Directorate of Surveys and Land Information
Geohydrological perspective • aquifer types • recharge • potential • vulnerability	Geohydrological maps • national groundwater maps • harvest potential map • national groundwater vulnerability map • 1:500 000 geohydrological maps	WRC; Directorate of Geohydrology
Geohydrological data • borehole yields • geohydrological parameters (T, K, S) • aquifer thickness • static water level contour map • groundwater quality • monitored water levels • monitored groundwater quality	Geohydrological data • national groundwater database • hydrochemical database • geohydrological reports	Directorate of Geohydrology; DWAF regional offices; WRC; Local authorities; Consultants; Other
Rainfall • annual • monthly • spatial distribution across catchment	Climatic data	Weather Bureau; WR90; S.A. Atlas of Agrohydrology and Climatology
Population	Population data	Central Statistical Services

T = transmissivity; K = hydraulic conductivity; S = storage.

19.6 ROLES AND RESPONSIBILITIES AT THE WORKSHOP

At the workshop, it is the responsibility of the attending geohydrologist to participate as fully as possible by providing:

- explanation and interpretation of available geohydrological data and information;

- expert judgement on the necessary management of groundwater to achieve the required EMC (Chapter 11);
- level of confidence of any advice or recommendations;
- description of any future information and work requirements.

19.7 ROLES AND RESPONSIBILITIES AFTER THE WORKSHOP

After the workshop, a key responsibility of the geohydrologist is to review any relevant information emanating from the other specialists to ensure a high degree of compatibility between the data sets.

19.8 EXAMPLE OF TERMS OF REFERENCE

The Terms of Reference for geohydrological input during BBM assessments varies according to the perceived influence of groundwater on the river system, the importance of the river and the available budget. However, the following essential tasks should be included.

- Collect appropriate geohydrological information to prepare a report for the workshop starter document describing the characteristics of the prevailing aquifer system and the role groundwater plays in sustaining the river and related ecosystems. Particular reference should be made to:
    - geology;
    - aquifer properties including type, thickness, transmissivity and storativity;
    - groundwater level (depth to water, hydraulic gradient, direction of flow);
    - groundwater recharge mechanisms and quantification thereof;
    - surface-groundwater interactions and the role groundwater plays in supporting the river, particularly during low flows;
    - groundwater quality;
    - groundwater contamination;
    - groundwater use, importance as a resource and any impacts resulting from such use;
    - aquifer classification;
    - aquifer vulnerability.
- Attend and participate in the BBM Workshop.
- Take part in relevant post-workshop activities, including documentation of the geohydrological component, collection of additional data, refinement of the report for the starter document and establishment of a required monitoring programme.

19.9 MINIMUM AND OPTIMUM SPECIALIST TRAINING

An understanding of the geohydrological regime and its links with surface water bodies requires a high degree of specialist geohydrological knowledge, expertise and experience. As the BBM requires a degree of professional judgement, a relatively experienced geohydrologist (M.Sc. with greater than 10 years experience) or senior geotechnician (B.Tech. with 15 years experience) should be appointed. If possible, this specialist should have experience in the geohydrological terrain being assessed, as well as a working knowledge of hydrology, hydraulics, geomorphology and related topics.

The appointed specialist should also undertake the hydrocensus, as this allows familiarisation with the study area. Field data can be collected by less qualified and experienced staff, such as junior geohydrologists or geotechnicians with five years experience. The senior specialist, however, should supervise such work.

19.10 POTENTIAL PITFALLS

A lack of data remains the greatest hurdle to providing sound geohydrological input into assessments of environmental flows. As drilling is the only direct means of gaining access to the geohydrological regime, measurement of aquifer parameters will always be limited. Continued efforts are required to establish a sufficiently well-populated national geohydrological database of good quality data. Further, dissemination of knowledge and experience gained during all geohydrological assessments, and in particular those related to the Reserve and EFAs, is essential. Report and paper publication as a means of information exchange between professionals is vital.

Few geohydrologists have experience in providing input into EFAs. As the type of information required and form of presentation are different to those for, say, groundwater supply or contamination projects, the ability of geohydrologists to convey the required information to non-groundwater specialists could be problematic. Development of a pool of experienced geohydrologists capable of providing the required input is therefore required.

Quantification of recharge and the interaction between surface and ground waters remain major technical limitations. Only recently have hydrological and geohydrological specialists undertaken integrated assessments, and this has been largely because it is required for EFAs and Reserve determinations. A number of issues have emerged from this integration that require resolution. These include: conceptual understanding of the interaction; a common terminology; and quantification, either by baseflow separation or recharge estimation, of that part of the groundwater which sustains river flow.

Efforts to establish a national geohydrological monitoring programme were initiated by DWAF in the mid-1990s. As a result, the surface water monitoring networks contain a limited number of monitoring stations for groundwater level and water chemistry. In places, more detailed local monitoring may have taken place, but available information is woefully inadequate. Development of the national monitoring programme, and implementation of Reserve and EFR-related monitoring are thus urgently required.

19.11 FURTHER DEVELOPMENTS

Inclusion of groundwater considerations in the BBM is still in its infancy. A wide range of further work and development is required, including initiatives to overcome the above pitfalls.

Some of the more important areas requiring development include:

- an accepted common terminology;
- recharge quantification methods;
- baseflow separation techniques;
- quantification of surface-groundwater interaction;
- demarcation of **groundwater abstraction restriction zones** around aquatic ecosystems critically dependent on groundwater.

Very little is known about the impact of groundwater abstraction on the environment. Isolated anecdotal accounts of impacts have been reported (Hatton & Evans 1998; Scott & Le Maitre 1998; DWAF 1999d), but these have not been supported with evidence. It is critical that reported impacts are investigated and a database of such impacts maintained. The investigation and licensing requirements of the Water Act should facilitate a better future understanding of such impacts and associated risks.

19.12 MONITORING

Groundwater monitoring is a critical component of assessing the geohydrological component of EFAs. This includes both regional and site-specific monitoring.

The national groundwater monitoring programme and need for its accelerated implementation are addressed in Section 19.9. No guidelines for monitoring at and around BBM sites are available at this stage. Realistic and affordable requirements in this regard should emerge as increased numbers of BBM assessments are undertaken, and as understanding about the dependence of aquatic ecosystems on groundwater develops.

Monitoring of fluctuations in groundwater level around ecologically critical aquatic habitats is a key management requirement. Installation of shallow wellpoints and boreholes at such refugia should be mandatory, particularly if significant groundwater abstraction takes place nearby.

19.13 CONCLUSIONS

The role of groundwater in sustaining aquatic ecosystems is becoming apparent. However, the volume of groundwater is less important than its ability to sustain surface water habitats during dry periods or prolonged periods of drought.

Inclusion of geohydrological expertise in BBM applications is hence both warranted and required. As the BBM uses existing data and limited field data collection, professional judgement is often required. A high level of both geohydrological expertise and experience thus is required to ensure appropriate geohydrological input.

A number of limitations in knowledge and data have been recorded above, including those pertaining to recharge quantification, baseflow separation and groundwater monitoring. It is critical that research be undertaken to address these limitations, and formal mechanisms be put in place to capture knowledge and experience gained when undertaking assessments using the BBM.

20. COORDINATION OF THE BUILDING BLOCK METHODOLOGY STUDY AND PRODUCTION OF THE WORKSHOP STARTER DOCUMENT

Delana Louw

20.1 COORDINATION OF THE BUILDING BLOCK METHODOLOGY STUDY

The BBM coordinator oversees all aspects of the study in which the BBM is applied, and forms the link between the study team and the client. The most important duties are to:

- compile Terms of Reference for the study as a whole, and for each specialist, in consultation with the project leader;
- ensure that there is adequate liaison between the specialists;
- ensure that the work of specialists with related disciplines is compatible (e.g. hydraulics, habitat integrity and geomorphology);
- arrange all field activities, and ensure that the necessary people and equipment are on site;
- make and fund all travel arrangements for field trips, including food, vehicle and accommodation needs;
- create a timetable, with deadlines for completion of all tasks, and ensure that it is adhered to;
- arrange dates and venues for the Planning Meeting and the BBM Workshop, and all facilities required there;
- make all travel arrangements for these meetings;
- regularly update the status of the project, for report back to the client.

Initiation of the study has been dealt with in Chapter 6, and site selection in Chapter 7. The coordinator ensures that all facilities for these activities are in place, and that the habitat integrity assessment takes place in time for the Planning Meeting.

When the specialist studies of the river begin, the coordinator ensures that team members visit the sites together whenever possible. Specialists who may wish to work together could be the survey team, the hydraulic modeller, the vegetation specialist, the geomorphologist and the fixed-point photographer. The survey team may make several visits, to take field measurements at several different discharges. These will aid development of realistic stage-discharge relationships for each cross-section. Several specialists may wish to ensure that ecosystem features of importance to them are included on the surveyed cross-sections.

The biological studies may take place independently, but discharge should be measured during each site visit. This allows data on species' distributions to be linked to hydraulic conditions and available habitat.

An experienced BBM team will complete data collection with little trouble, but the coordinator has to be able to guide specialists unfamiliar with the concepts and practicalities of the approach. The ensuing workshop can be heavily compromised by inappropriate data, and so it is a sound investment to appoint an experienced coordinator to run the study.

As the studies draw to completion, the coordinator ensures that summary chapters (brief reports) are written by each specialist, for inclusion in the starter document for the BBM Workshop (Section 20.2).

20.2 THE WORKSHOP STARTER DOCUMENT

The starter document has four main purposes:

- to document all specialist activities leading up to the workshop;
- to allow the specialists to synthesise their data and knowledge, in preparation for their contributions at the workshop;
- to inform all team members of ecosystem aspects other than their own;
- to stand as a permanent record of the characteristics of the ecosystem at that time; for many rivers this will be the only such comprehensive record in existence.

Each chapter in the document is restricted in length, usually to about ten pages, so that all workshop participants can read all contributed chapters before arriving at the workshop. This negates the need for a lengthy presentation of each chapter at the workshop, which would encroach on the limited time available for consideration of the EFR. Further transfer of knowledge between specialists is catered for during the site visit, which is an early part of the workshop (Chapter 21).

The specialists may wish to consult larger data sets during the workshop, and are encouraged to bring computers, software packages and any other facility that could aid their deliberations. The hydrologist and hydraulic modeller in particular, bring much of their data to the workshop as computer files. They can then answer queries accurately and efficiently, and present data in a variety of ways as the need arises (Chapters 12 & 13).

20.2.1 Contents of the starter document

An example of the Table of Contents of a starter document is given in Table 20.1. The contents may vary from project to project, but some (shown in bold) are routinely included. Items with an asterisk are the subject of other chapters in this manual, in which details of their required contents are given.

20.2.2 Compilation of the starter document

The document is compiled by the BBM coordinator from the individual chapter contributions. Specialists are reminded about two weeks before their chapters are due. Each workshop participant receives a copy about three weeks before the workshop, for study before the workshop.

Table 20.1 Example of the Table of Contents of a starter document for a BBM Workshop. Contents shown in bold are routinely included. Details of the required contents of items with an asterisk are described in the corresponding chapters of this manual.

TABLE OF CONTENTS

1. INTRODUCTION
  1.1. Programme *
  1.2 Participants *
  1.3 Venue

2. BACKGROUND TO THE PROPOSED WATER-RESOURCE DEVELOPMENT AND ITS OPERATION

3. COMPILATION OF THE EFR
  3.1 Link between the ecological Reserve and the EFR
  3.2 BBM PROCESS *
  3.3 BBM Planning Meeting *
  3.4 BBM sites *
  3.5 Problems experienced during this study

4. ECOLOGICAL MANAGEMENT CLASS
  4.1 Assessment process *
  4.2 Present state: habitat integrity *
  4.3 River importance *
  4.4 Ecological Management Class

5. SPECIALIST STUDIES
  5.1 Fluvial geomorphology *
  5.2 Riparian vegetation *
  5.3 Water quality *
  5.4 Fish *
  5.5 Aquatic invertebrates *
  5.6 Hydrology *
  5.7 Hydraulics *
  5.8 Social dependence on the riverine ecosystem *

20.3 THE SITE VISIT DOCUMENT

It has been found that a summary of some of the data in the starter document, and some additional information, are useful references during the team visit to the sites at the start of the BBM Workshop. A site visit document is thus recommended, in which the following usefully can be included:

- a general map of the area, so that specialists can orientate themselves within the catchment during travel to the sites;
- a diagrammatic map of the study area (e.g. Figure 12.1);
- the habitat integrity map, with the instream and riparian classes illustrated (e.g. Figure 8.1);
- the programme for the site visit;
- for each BBM site:
    - a summary page of hydrological data showing characteristics of ecological importance, such as seasonal and yearly variability in daily flows and monthly volumes;
    - a plan view of the site with important habitats illustrated, drawn by the coordinator, geomorphologist or one of the ecologists;
    - one or more cross-sectional profiles, showing the surveyed positions of vegetation zones or specific riparian plant species;
    - scanned photographs of the site, with the positions of the cross-sections shown;
    - the hydraulic information (depths, velocities and stage, all related to discharge).

21. THE BUILDING BLOCK METHODOLOGY WORKSHOP AND REPORT

Delana Louw

21.1 INTRODUCTION

The purpose of the BBM Workshop is to bring together the full team of specialists, to participate in a structured process for defining the EFR. The process does not take into account the capability of planned or existing water-resource developments for supplying the described EFR, but merely aims to state the flow requirements for meeting the designated EMC and objectives (Chapter 11).

The workshop has some standard components, which are described in Section 21.3, but, as long as the concepts of the BBM are adhered to, the programme can be amended in different ways to suit different assessments.

21.2 PARTICIPANTS AND VENUE

Workshops in the past have used either one group of specialists, or two, with all disciplines duplicated and the two groups considering different BBM sites in the study area. Recently, the one-group approach has been favoured because, *inter alia*, the demand countrywide on a limited number of specialists was too great, and the two-group approach often required input from specialists not involved in the BBM study or unfamiliar with the river. Wherever possible, the client attends the workshop, to gain an understanding of the process used. Observers are, however, strictly limited, in order to maintain the dynamics of a small group. Experience has shown that a maximum of 16 participants should be involved, including the specialists (usually about 11) directly involved in setting the EFR.

The workshop typically takes place in an isolated conference venue in the study area. This allows all team members to visit each BBM site together, and to enhance their understanding of the nature of the river and its catchment. Also, isolating the participants in a secluded venue in the catchment of concern encourages focused thinking and a vibrant work ethic, where discussions on the river spill over into leisure hours (King & Louw 1998).

The venue should have the following conference facilities available:

- a conference room able to seat 16 persons in a U-shaped arrangement;
- television and video cassette recorder with remote control, for showing the edited video taken during the habitat integrity survey;
- overhead projector;
- slide projector;
- screens;
- flipcharts;
- sufficient extension leads, power points and adaptors for a variety of computers and printers.

21.3 WORKSHOP PROGRAMME

The workshop programme (Table 21.1) is drawn up by the coordinator well before the workshop. This is sent to all participants for comment and to alert them to what is required from them. In Table 21.1, the example programme has been divided into four sessions, each consisting of related actions which are detailed below.

21.3.1 Session 1: site visit

The site visit is a crucial part of the workshop, when specialists share perceptions of each BBM site with the rest of the team. All sites (usually four) are visited, with about two hours spent at each. The following activities take place at each site.

- Discussion of the location and nature of each hydraulic cross-section, and the physical habitats represented by each of them.
- A short (5 minute) presentation by each specialist on relevant points from their studies. Important features are pointed out, and the effect on them of different magnitude discharges is discussed.
- The water level is recorded, to allow calculation of the discharge occurring during the site visit.
- If the water level is sufficiently different to that recorded on any previous site visit, the discharge is measured to provide extra calibration data for the hydraulic model.
- Photographs (polaroid, if necessary) are taken from the established fixed points, as extra reference material for workshop discussions.
- The team members are given an opportunity to investigate aspects of the site in smaller groups.

Table 21.1 Example of a BBM Workshop programme.

DAY 1: TUESDAY 27 OCTOBER 1998

		SITE VISIT (DETAILED PROGRAMME IN SITE VISIT DOCUMENT)
09:00		**MEET AT BBM SITE 1** SITE INSPECTION, DISCUSSIONS & INVESTIGATION

DAY 2: WEDNESDAY 28 OCTOBER 1998

07:00	[10]	INTRODUCTION, PROGRAMME & DOCUMENTATION
07:10	[10]	HYDROLOGY OF THE BBM SITES
07:20	[30]	HYDROLOGICAL CLASSIFICATION OF SYSTEM: PERCENTAGE OF ASSURANCE OF MAINTENANCE FLOW VERSUS DROUGHT FLOW
07:50	[1h10]	ECOLOGICAL MANAGEMENT CLASS: PROCESS, ECOLOGICAL & SOCIAL IMPORTANCE, & FINALISATION OF CLASS
09:00	***[60]***	***BREAKFAST***
10:00	[30]	CONTINUE WITH ABOVE
10:30	[20]	CONFIDENCE IN SITES FOR DETERMINING EFRs & SELECTION OF SITES FOR DETAILED EFR
10:50	[2h]	DETERMINATION OF MAINTENANCE & DROUGHT EFRS FOR SELECTED SITE FOR BASE/LOW FLOWS
12:50	***[40]***	***LUNCH***
13:30	[3h]	CONTINUE WITH PREVIOUS SESSION
16:30	[60]	DETERMINATION OF MAINTENANCE & DROUGHT EFRs FOR SELECTED SITE FOR HIGH FLOWS
17:30	***CLOSURE***	

DAY 3: THURSDAY 29 OCTOBER 1998

07:00	[2h]	CONTINUE WITH PREVIOUS SESSION
10:00	[2h30]	DETERMINATION OF MAINTENANCE & DROUGHT EFRs FOR SECOND SELECTED SITE FOR BASE/LOW FLOWS
12:30	***[45]***	***LUNCH***
13:15	[2h]	CONTINUE WITH PREVIOUS SESSION
15:15	[2h]	DETERMINATION OF MAINTENANCE & DROUGHT EFRs FOR SELECTED SITE FOR HIGH FLOWS
17:15	***CLOSURE***	

DAY 4: FRIDAY 30 OCTOBER 1998

07:00	[20]	MATCHING OF RESULTS & RECOMMENDED CHANGES
07:20	[10]	EXTRAPOLATED RESULTS TO OTHER TWO SITES
07:30	[1h30]	CHECK OF EXTRAPOLATED RESULTS
09:00	***[60]***	***BREAKFAST***
10:00	[60]	RUNNING AND CALIBRATING IFR MODEL
11:00	[30]	CONFIDENCE RATING IN EFR RESULTS
11:30	[30]	FURTHER WORK
12:00	[30]	GENERAL STATEMENTS & THE WAY FORWARD
12:30	***CLOSURE***	

21.3.2 Session 2: preliminary workshop activities

Hydrology

The hydrologist makes a presentation of the following:

- the past and present hydrological character of the river;
- the hydrological models and other hydrological support services available via computer;
- the level of confidence in both measured and simulated hydrological data;
- the flow variability characteristics of the river and the expected level of assurance that maintenance flows will be designed for (for example, a strongly perennial river would be expected to need a higher assurance of maintenance flow than a semi-arid river).

The Ecological Management Class

The process followed for establishing the EMC should follow the format for a Reserve study.

- **PES**: The PES is described using one of the six classes A-F (Chapter 11). Each relevant specialist allocates each river reach to a class with justification of the allocation. Consensus is then sought on an overall class for the PES, which is not an average of all the individual assessments, but rather, is guided by driving variables such as availability of habitat.
- **River importance** (Chapter 10) is then considered as part of the deliberations for setting the protection class (EMC).
- An **EMC** from A-D (Chapter 11) is allocated by the team to each river section for which a PES has been described. These EMCs are then further translated into **RQOs**, which define the specific objectives that must be met in order to achieve the EMC.

A1-size templates (Tables 21.2a-c) can be provided for completion at the workshop, to aid the above process of assessing the PES (Table 21.2a), river importance (Table 21.2b) and the EMC (Table 21.2c).

Evaluation of the sites

Of the chosen and studied BBM sites, a reduced number may be addressed in detail in the workshop. An EFR for each of the other sites is derived by extrapolation from the sites considered in detail (Section 21.3.3). A detailed check on the adequacy of the extrapolated EFRs is then done, using the site information.

If all studied sites are not to be considered in detail, then they are all evaluated to ascertain which are mostly likely to lead to a high confidence EFR. In order to make this assessment, each specialist rates each site, using a custom-designed assessment table (Table 21.3). The ratings are not added and averaged, but are used as a group when selecting the sites for comprehensive assessments. Accurate hydraulic measurements and high confidence hydraulic modelling will often be the overriding factors in the choice of a site, as high quality ecological data on required hydraulic conditions can be negated by inaccurate hydraulic information on the equivalent discharge value. The geographical placing of sites is also a consideration. For example,

Table 21.2a Example of a template used in the assessment of Present Ecological State, for the Mhlatuze BBM study.

	COMPONENT		**Goedertrouw to Mhlathuze Weir**	**Mhlathuze Weir to Estuary**
PRESENT STATE	**FISH**	Class		
		Motivation		
	AQUATIC INVERTEBRATES	Class		
		Motivation		
	RIPARIAN VEGETATION	Class		
		Motivation		
	FLUVIAL GEOMORPHOLOGY	Class		
		Motivation		
	WATER QUALITY	Class		
		Motivation		
	SOCIAL	Class		
		Motivation		
	HABITAT INTEGRITY INSTREAM	Class		
		Motivation		
	HABITAT INTEGRITY RIPARIAN	Class		
		Motivation		

Table 21.2b Example of a template used in the assessment of river importance, for the Mhlatuze BBM study.

	COMPONENT		Goedertrouw to Mhlathuze Weir	Mhlathuze Weir to Estuary
RIVER IMPORTANCE	**ECOLOGICAL**	Rating		
		Motivation		
	SOCIO/CULTURAL	Rating		
		Motivation		
	ECONOMIC	Rating		
		Motivation		

Table 21.3 Example of a site selection table for the purpose of selecting two of the four BBM sites which will have the highest confidence overall for determining EFRs.

Confidence rating:

None = 0; Low = 1; Low-Medium = 2; Medium = 3; Medium-High = 4; High = 5
L = Low Flows; H = High Flows

BBM SITES		**EFR COMPONENT**								**EVALUATION**
		HYDRAULICS	**HYDROLOGY**	**FISH**	**VEGETATION**	**GEOMORPHOLOGY**	**AQUATIC INVERTEBRATES**	**WATER QUALITY**	**AIDS/ PHOTOS**	
1	**L**									
	H									
2	**L**									
	H									
3	**L**									
	H									
4	**L**									
	H									
TWO BEST SITES		EFR	EFR	EFR	EFR	EFR	EFR	EFR	EFR	
		EFR	EFR	EFR	EFR	EFR	EFR	EFR	EFR	

Table rules:

- General: Evaluate each site from your specialist viewpoint and determine which sites have the most potential for determination of high quality EFRs. If you evaluate the sites as low, NO motivations are necessary as these are reflected in your contribution to the BBM site selection paper.
- Evaluation: If the numbers are added in the evaluation table, the analysis of the totals must be undertaken with care. The highest total does NOT necessarily represent the best BBM site, as some of the criteria such as hydraulics should be weighted.

selection of the two most upstream sites probably would not provide the best basis for extrapolation to a number of downstream sites.

21.3.3 Session 3: setting the Environmental Flow Requirement

Setting the Environmental Flow Requirement for the two selected sites

The facilitator decides on the details of the process to be followed. An overview of the procedures is given below.

Low flows and floods are recommended for both maintenance years (years of ‘normal’ rainfall, when the full suite of ecological functions and processes should be expected - i.e. the Maintenance EFR, when the designated EMC and objectives should be met) and drought periods (when the flows are designed to allow for the survival of species and important ecosystem processes - i.e. the Drought EFR). For example, during maintenance years it would be expected that all species would potentially be able to breed, whereas in drought years, there might be a number of sensitive species for which breeding conditions would not be met.

The same approach is used in both cases, typically starting with the drought periods.

- The two months with the highest and lowest natural baseflow are selected, with reference to the hydrological record.
- A recommended low flow value (in $m^3 s^{-1}$) for each of these two months (termed the ‘anchor’ months) is decided upon, and together these define the limits of the range of low flows for the other months. The term low flow generally is used in preference to baseflow, to avoid any inappropriate inferences associated with the hydrological context of the latter term. However, within this process, they mean much the same.
- A low flow value is then estimated by extrapolation for each of the other calendar months, guided by the hydrological record. This extrapolation is undertaken by the hydrologists and checked by the ecologists.
- For the low flow values for the two ‘anchor’ months, each specialist records the hydraulic conditions (channel inundation level, velocity, depth) that should be met by these flows, and the reasons why such conditions are needed. The reasons are recorded as primary or secondary motivations. Specialists needing higher flows than others provide the primary motivations. Secondary motivations, where somewhat lower flows would be acceptable, support the primary ones.
- After each month’s low flow is agreed on, it is checked against the hydrological record to ensure that it is realistic. ‘Normal’ or ‘average’ hydrological years are used to check flows for maintenance years, while the driest years on record are used to check flows for drought years.
- A range of high flows is then recommended, mostly to occur in the wet season. High flows encompass freshes (small peaks of flow in the dry season), and small, medium and large floods. The high flows required are described in terms of their instantaneous peak, duration, return period and timing. As the hydrological data are given as mean daily discharges, the recommended peak values are converted to appropriate lower daily values by the hydrologist to match the record. It should be ensured that the flood requirement is realistic, by its comparison with the natural flow regime.
- The shape of the recommended floods is based on the shape of the natural hydrograph.

- When calculating the percentage of the MAR incorporated into the EFR, it should be ensured that the volume of low flow occurring in the flood events is not included both there and in the low flow figures.
- The resulting recommended high and low flows for each BBM site, for maintenance and drought conditions are documented in the EFR table (Table 21.4).

Matching results for the sites chosen for detailed study

After the EFRs for the BBM sites chosen for the detailed assessment have been set, they are checked by the hydrologist for hydrological compatibility. Any inconsistencies are discussed by the group, and one or more sites may be adjusted accordingly.

The extrapolation procedure

The hydrologist uses the flows recommended for the considered sites, to derive extrapolated flow regimes for the sites for which detailed flow assessments were not made. The extrapolated flows are used to describe the hydraulic conditions that would result at the latter sites. The specialists then use collected data and information to assess whether or not the extrapolated flow regimes would facilitate achieving the designated EMC and objectives for the relevant reaches. If adjustments of the extrapolated flow regimes seem appropriate, these are first checked against the EFRs for the considered sites.

The Instream Flow Requirement Model

The IFR Model (see Sections 12.6 & 12.7) is run for the BBM site that is considered to be most important. During this session, the specialists have the opportunity to influence calibration of the model, by judging, for instance, whether the maintenance and drought periods occur in the right kinds of proportions. The output of this session is the final recommended EFR. It then can be linked to the **Water Resources Yield Model** (WRYM; Section 22.3), if required.

21.3.4 Session 4: finalising the workshop

Assessing the confidence in the recommendations

Each specialist attaches a confidence evaluation to his or her recommendations (Table 21.5), with an explanation. The water manager takes these into consideration when making decisions on water allocations.

Further work

Recommendations for further investigations are made. These usually reflect the areas of low confidence highlighted in Table 21.5. The investigations usually fall into three categories (King & Louw 1998):

- short-term work required to refine the recommended EFR;
- medium-term research required to improve the methodology;
- long-term fundamental research on subjects about which little is known.

Table 21.4 Example of an EFR table for BBM site 1 on the Mhlatuze River, at Stewart's Farm (from DWAF 2000). Virgin MAR = 185 x 10^6 m^3 (MCM). Draft figures are presented.

	OCT		NOV		DEC		JAN		FEB		MAR	APR	MAY	JUN	JUL	AUG		SEP		TOTAL X 10^6 m^3	% of MAR
EFR MAINTENANCE LOW FLOWS																					
FLOW (m^3 s^{-1})	0.8		1.1		1.5		2		2		2	1.6	1.1	0.8	0.6	0.4		0.6			
DEPTH (m) section	0.36		0.39		0.41		0.45		0.45		0.45	0.42	0.39	0.36	0.33	0.3		0.33			
FDC% (VIRGIN)	64		79		87		71		78		74	72	76	76	68	73		51			
VOLUME (x 10^6 m^3)	2.1		2.9		4		5.4		4.8		5.4	4.1	3	2.1	1.6	1.1		1.6		38.1	20.6
EFR MAINTENANCE HIGH FLOWS																					
FLOW (Instantaneous peak, m^3 s^{-1})	4	2	2	2	13	3	13	4	45	4	13	4				4	1.2	13	1.2		
DEPTH (m) section	0.53	0.45	0.45	0.45	0.75	0.49	0.75	0.53	1.53	0.53	0.75	0.53				0.53	0.4	0.75	0.4		
DURATION (days)	2	2	2	2	3	2	3	2	2	2	3	2				2	2	3	2		
FDC% (VIRGIN)	28	45	64	64	12	57	12	44	5.8	56	17					6.6	28	3	34		
VOLUME (x 10^6 m^3)	0.5		0.2		2		2		7		1.7	0.3				0.5		3.3		17.6	9.6
	OCT		**NOV**		**DEC**		**JAN**		**FEB**		**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**		**SEP**		**TOTAL X 10^6 m^3**	**% of MAR**
EFR DROUGHT LOW FLOWS																					
FLOW (m^3 s^{-1})	0.3		0.5		0.6		0.6		0.55		0.5	0.7	0.3	0.2	0.15	0.1		0.2			
DEPTH (m) section	0.28		0.31		0.33		0.33		0.32		0.31	0.3	0.28	0.25	0.23	0.2		0.25			
FDC% (VIRGIN)	79		94		100		100		97		98	100	99	95	94	80		51			
VOLUME (x 10^6 m^3)	0.8		1.3		1.6		1.6		1.3		1.3	1	0.8	0.5	0.4	0.3		0.7		11.6	6.3
EFR DROUGHT HIGH FLOWS																					
FLOW (Instantaneous peak, m^3 s^{-1})	0.6		1.2	1	1.5		1.9		13	1.1	1							0.4			
DEPTH (m) section	0.33		0.4	0.38	0.41		0.44		0.75	0.39	0.38							0.3			
DURATION (days)	2		2	2	2		2		3	2	2							2			
FDC% (VIRGIN)	76		78	81	87		74		24	92	87							73			
VOLUME (x 10^6 m^3)	0.02		0.08		0.06		0.09		2		0.03							0.01		2.29	0.01

Table 21.5 **Example of a completed EFR result confidence table, for attaching a confidence value to the results of the EFR set, based on the different specialist viewpoints.**

Confidence rating:

None = 0; Low = 1; Low-Medium = 2; Medium = 3; Medium-High = 4; High = 5

L = Low Flows; H = High Flows

Note:

- Confidences are only attached to low or high flows where motivations are supplied. If, for example, motivations were not supplied for low flows as might be the case for geomorphology, no motivation for confidence for low flows is supplied.
- Motivations for evaluations are supplied whenever necessary, specifically for low evaluations.

BBM SITES		EFR COMPONENT					
		AMPHIBIANS	FISH	RIPARIAN VEGETATION	GEOMORPHOLOGY	AQUATIC INVERTEBRATES	WATER QUALITY
1	L	5	4	-	-	4	-
	H	5	3	4	4	4	-
3	L	5	4	-	-	4	4
	H	5	3	3	4	4	-

Statements

The final activity is a discussion session on the workshop, and a debriefing. Any additional statements that participants wish to make individually or collectively are noted for inclusion in the workshop report, and discussed if necessary.

21.4 ROLE OF THE FACILITATOR DURING THE WORKSHOP

An experienced river scientist who has extensive experience in EFAs in general and the BBM in particular, should act as facilitator. The duties are to lead and guide the group of specialists through their various considerations to a consensus recommendation on the EFR for each site.

21.5 ROLE OF THE COORDINATOR DURING THE WORKSHOP

The coordinator supports the facilitator by, for example:

- helping specialists to understand and use the general aids available;
- ensuring that all information available is being accessed as needed;
- working with the report writer to check all the data tables filled in by specialists, for completeness, correctness and legibility;
- making lists of issues on flip charts, as required by the facilitator;
- keeping track of changing motivations and data summaries during the matching and extrapolation exercises;
- recording issues raised in the workshop for later discussion, and ensuring they are addressed.

21.6 THE WORKSHOP REPORT

A report is written of the workshop activities, focusing on conclusions, a record of decisions that led to them, and details of the actual recommended EFRs (Table 21.6). The motivations supplied for each flow by all the specialists are provided as appendices. An experienced river scientist, preferably an ecologist with a substantial understanding of EFAs, should write the report.

Table 21.6 Example of the Table of Contents for a BBM Workshop report, for the Mhlatuze BBM study (from DWAF 2000).

Table of Contents

1. Introduction

2. The Reserve
2.1 The ecological Reserve
2.2 The link between the ecological Reserve (quantity) and the EFR
2.3 The environmental flow methodology: the BBM
2.4 Classification of water resources

3. BBM sites
3.1 Purpose of BBM sites
3.2 Selection of BBM sites
3.3 BBM sites: locality, advantages and disadvantages
3.4 Evaluation of BBM sites

4. Data used for EFR determination
4.1 Biophysical information (habitat integrity, fish, aquatic invertebrates, riparian vegetation, geomorphology, etc.)
4.2 Others (hydraulics, hydrology, water quality)

5. EFR results - Goedertrouw Dam to Mfule (BBM site 1)
5.1 Reference Conditions
5.2 Present Ecological State
5.3 Ecological and social importance
5.4 Ecological Management Classes and associated flow requirements

6. EFR results - Mfule to Mhlathuze Weir (BBM sites 2 and 3) (As above)

7. EFR results - Mhlathuze Weir to estuary (BBM site 4) (As above)

8. EFR results - confidence

9. Final EFR results

10. Monitoring and further work

APPENDICES
A: BBM site selection
B: Habitat integrity
C: Fish
D: Aquatic invertebrates
E: Riparian vegetation
F: Fluvial geomorphology
G: Social aspects
H: Hydraulics
I: Hydrology
J: Workshop programme
K: EFA participants
L: Photopoint monitoring
M: Motivations

22. POST-WORKSHOP SCENARIO ASSESSMENT AND IMPLEMENTATION OF THE ENVIRONMENTAL FLOW REQUIREMENT

Delana Louw and Denis Hughes

22.1 BACKGROUND

The BBM has three main phases:

- preparation for the BBM Workshop;
- the BBM Workshop;
- post-workshop linking of environmental and engineering concerns.

Although the third and final phase was recognised early in the evolution of the methodology, it is still the least developed part of the process. There are three main reasons for this.

- Most development of the BBM has occurred in real water-resource developments funded by the national government department responsible for water resources, DWAF. During the third phase of the BBM, the responsibility for the proposed development moves away from the DWAF directorates initially involved (Water Resources Planning and Project Planning), to other directorates such as Civil Design and Operation. Involvement by these directorates in EFAs has been minimal so far, and set procedures have yet to be designed.
- Development of the early phases of the BBM was aided significantly by being able to apply the process in many proposed developments that were still at the investigatory and planning stages. Only two proposed

developments for which an EFR was defined have moved to the point where implementation procedures are being developed (on the Sabie River, Mpumalanga, and Koekedouw River, Western Cape). Opportunities for developing phase three of the BBM in real water-resource projects have thus been limited.

- The information generated during the BBM process was not previously compatible with the tools used by water-resource design engineers. For example, the descriptions of EFRs included no statements about the frequency with which maintenance flows are required.

Despite these difficulties, the general form of what is being included in phase three of the methodology is outlined below.

22.2 THE NATURE OF PHASE THREE OF THE BUILDING BLOCK METHODOLOGY

Four further steps are undergoing development, to enable the EFR resulting from the BBM Workshop to be operationalised.

- Calculation of system yield under a range of scenarios, including one scenario that describes delivery of the EFR defined in the workshop.
- Design of a dam or other water-resource structure in a way that caters for both ecological and engineering considerations.
- Compilation of operating rules for the proposed development, to meet the water demands described by the scenario chosen by the water authority.
- Design and establishment of a monitoring programme, to track if the agreed environmental flows are being delivered, and the EMC and objectives being met.

22.3 SCENARIO BUILDING AND CALCULATION OF SYSTEM YIELD

In terms of the new Water Act, the priorities related to the use of water are illustrated by the ‘bucket diagram’ of DWAF (1999b) (Figure 22.1), and can be summarised as follows.

- **First priority***:* The Reserve, for basic human needs and ecosystem protection (including the EFR). These are the only two rights to water, and the Reserve may not be allocated to other users.
- **Second priority***:* International obligations.
- **Third priority***:* All other uses, which require authorisation.

The yield of a proposed development is the overall available volume of water in the river system under study, and its assurance of supply. It represents the available water remaining after the Reserve has been allocated and, in the BBM process, cannot be calculated until after the BBM Workshop. The model currently used by DWAF or their consultants to determine the yield is the WRYM (DWAF 1986). This is a complex system model, that can account for natural flows in a system and a wide variety of water uses, all defined with different levels of assurance of supply.

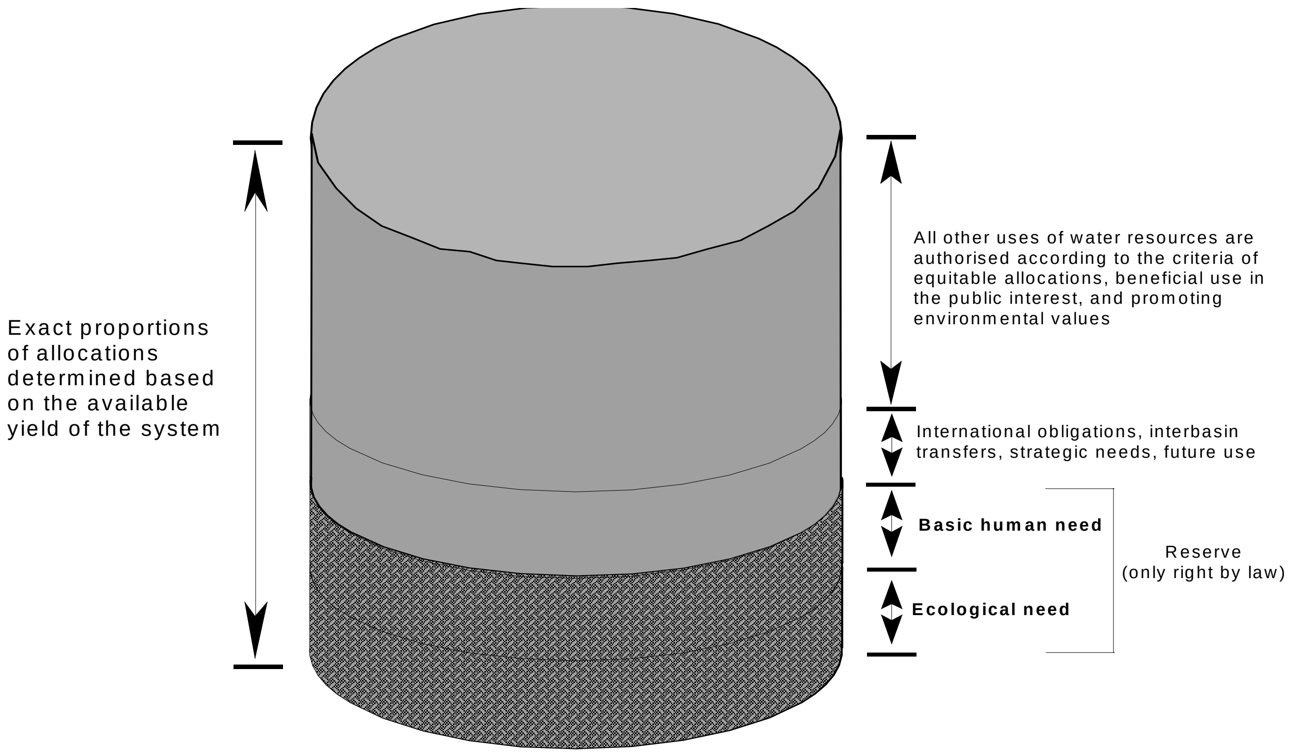


Figure 22.1 Bucket illustration of the priorities related to allocations for water use, including the allocations for the Reserve (from DWAF 1999b).

22.3.1 The link between the Environmental Flow Requirement and the Water Resources Yield Model

During early development of the BBM, the standard output from the workshop contained no information on the required levels of assurance of supply of different components of the EFR. For example, although the magnitude of maintenance low flows (baseflows) was specified for each calendar month, there was no indication of how to identify years when this might apply and years that should receive drought low flows (baseflows). Nor was it clear if, and when, low flow discharges could exceed the recommended maintenance low flow, or fall between it and the drought low flow. The simple stipulation was made that the switch should be linked to natural climatic triggers.

The upper part of Figure 22.2 illustrates a hypothetical low flow recommendation for the complete calendar year, and the lower part, four possible different assurance approaches to applying the low flow requirement for one of the months (February). Given this inherent uncertainty, the BBM was developed further to determine the percentage assurance rules for the required flows, so that these could be defined in a way that is compatible with the other water uses modelled with WRYM. The percentages of time that maintenance and drought flows should occur differ from river to river, depending on the rivers' sensitivity to flow variation (Hughes 1999). These percentages can be estimated from the characteristics of the hydrological regime, based on flow variability, but are checked against the perceptions of the ecological specialists. The output is a description of the assurance relationships (Figure 22.3), which is easier for the planner to use than the uncertainty illustrated in Figure 22.2. This process has been used in most applications of the BBM since 1997.

Another major concern was the link between the EFR and climate. One of the basic assumptions of the BBM is that the specified EFR for any river is supplied in a way that is linked to the current climate of that catchment. For example, a large flood should not be released downstream during a month when no rains occurred in the catchment. Also, droughts and maintenance low flows should occur, respectively, during naturally dry and normal periods. To facilitate this, the IFR Model was developed (Hughes *et al.*, 1997). Its application during and after the BBM Workshop is outlined in Sections 12.6 & 12.7.

The output from the BBM has therefore been extended, from the simple EFR table to a time series of design requirements (Figure 22.4) simulated by the IFR Model. A statistical summary is generated which provides (for each calendar month) the percentage of time that the modified flow regime is at, or above, maintenance, between maintenance and drought, or at drought levels. These are effectively the recommended assurance levels of the different flows and are also represented by an FDC (Figure 22.3).

Monthly total release volumes are generated for the complete time series, which are further analysed to determine more detailed assurance values for the full range of flows that form part of the recommended modified flow regime. The time series or assurance levels are then used in conventional water resources assessment and reservoir yield models (such as WRYM) to determine if the planned development can satisfy the expected abstraction demands as well as the EFR release requirement. The WRYM has recently been adjusted to accommodate the EFR, and to be compatible with the BBM results provided in the IFR Model format.

22.3.2 Interactive scenario development

With the models compatible, an interactive process of determining the impact on the yield and making any necessary adjustments is followed. The process (Figure 22.5) is based on the situation where the required yield is given prior to the EFRs being calculated, and the impact of the EFRs on the yield is then evaluated.

- **Supply EFR results to yield modellers**. The EFR results are provided in the format required by the WRYM and their correct use checked.
- **Assess impact of EFR on yield**. The yield modeller determines whether the EFR can be met with the proposed developments in place. If this is the case, the process ends here.
- **Develop alternative EFR scenarios**. If the EFR cannot be met without impact on the proposed development, the yield modeller provides some indication of which flow components of the EFR most impact yield. The modeller and key members of the BBM team then compile an appropriate range of scenarios by changing either the magnitude, frequency or duration of various flow components, or the assurance of these flows. The yield of each scenario is calculated. A comparison of a scenario EFR and the original one described in the BBM Workshop (Figure 22.6) is as follows:

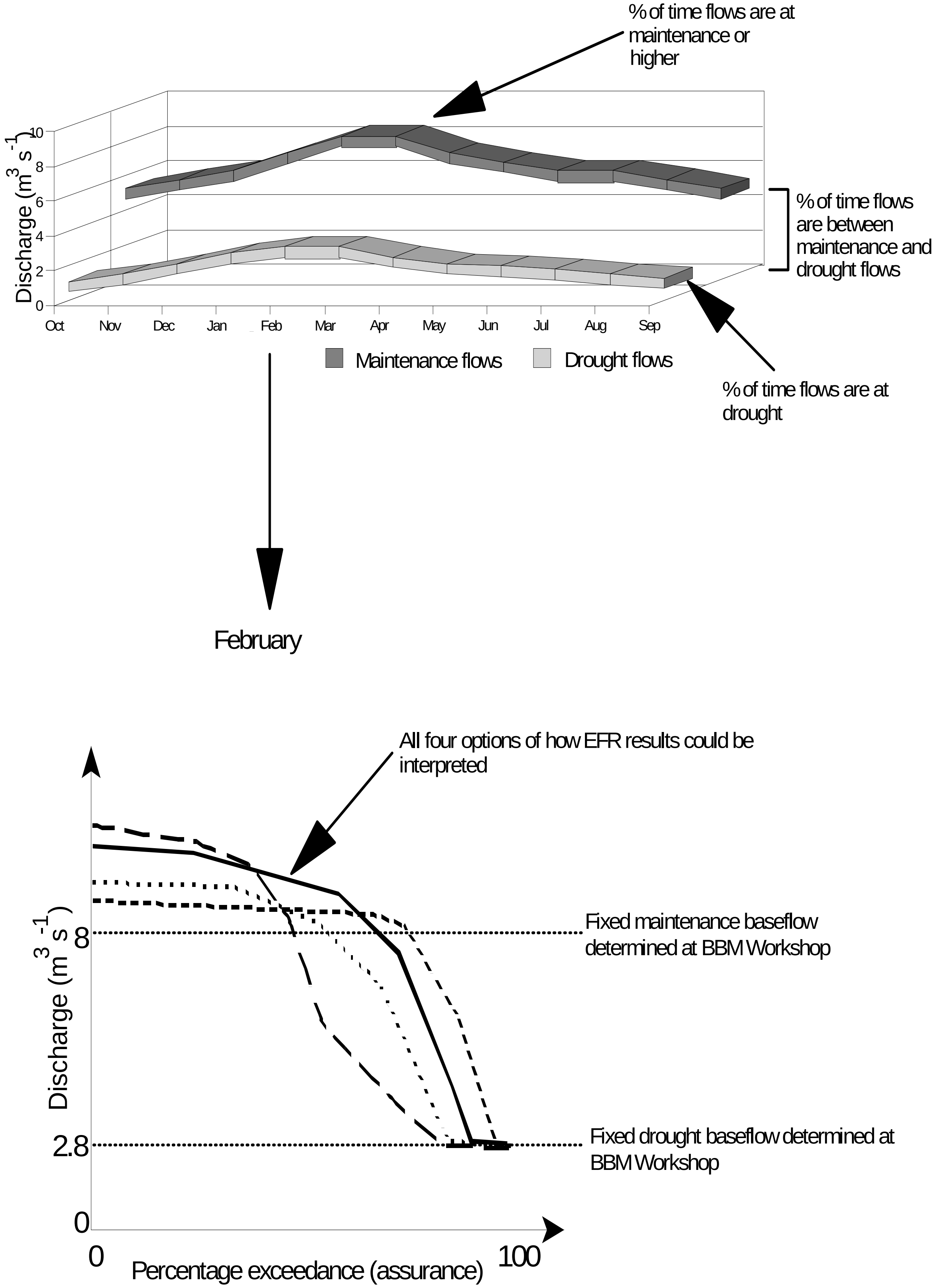


Figure 22.2 Baseflow EFR time series for one year and assurance curves for February, illustrating a range of possible solutions given the same BBM Workshop results.

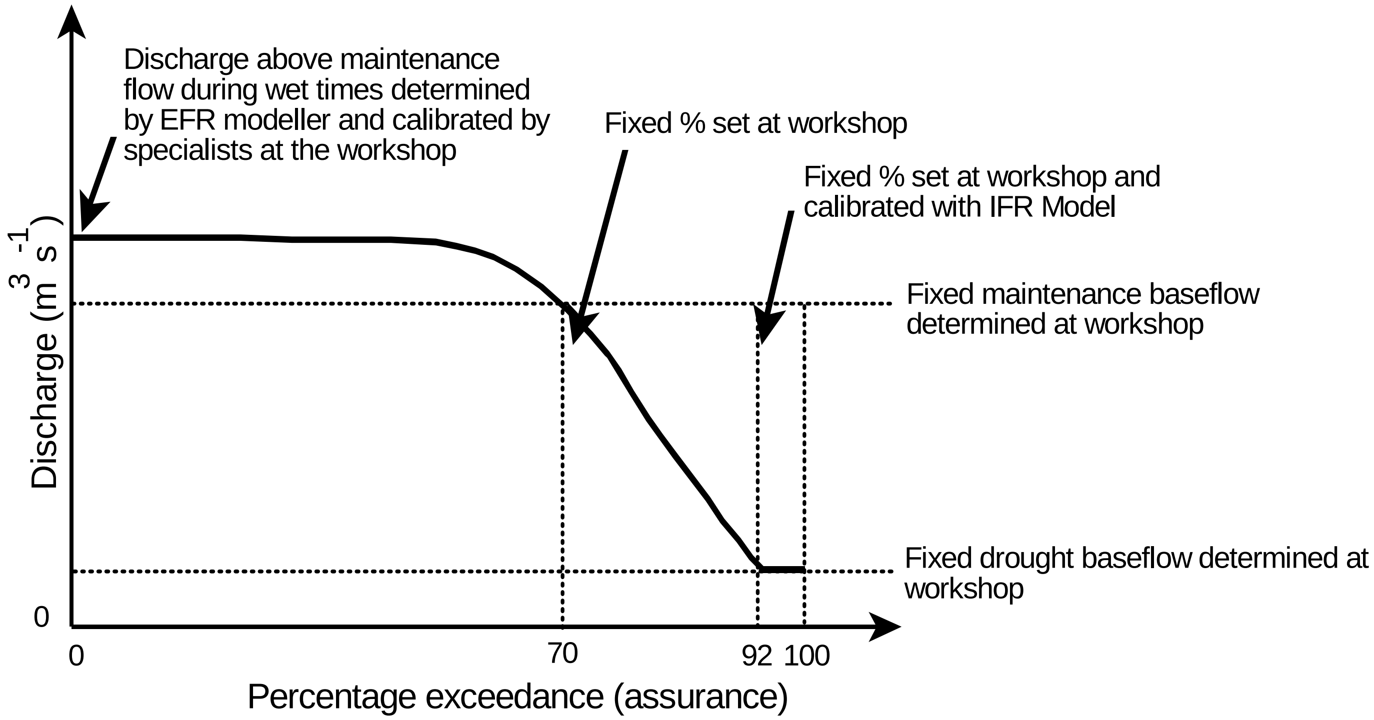


Figure 22.3 **Output of a BBM Workshop illustrated as an assurance curve. All numbers on the axes are hypothetical and will differ from river to river.**

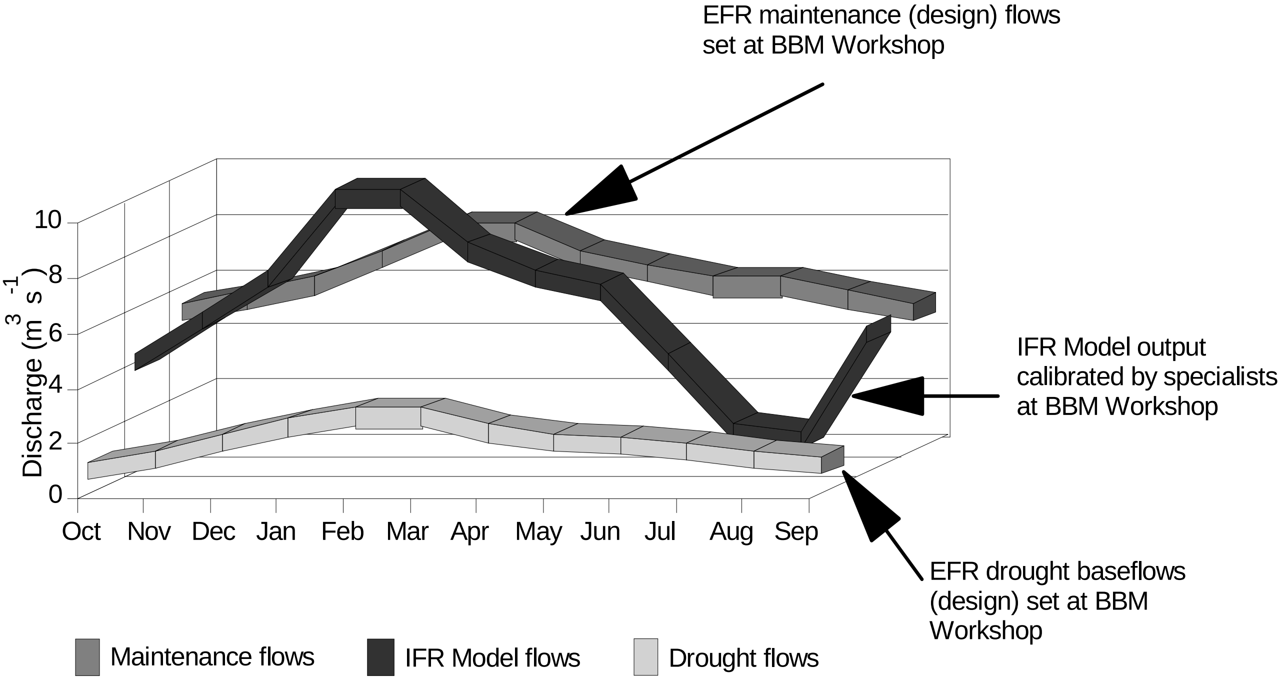


Figure 22.4 **Illustration of the output of the IFR Model as a time series for a single year.**

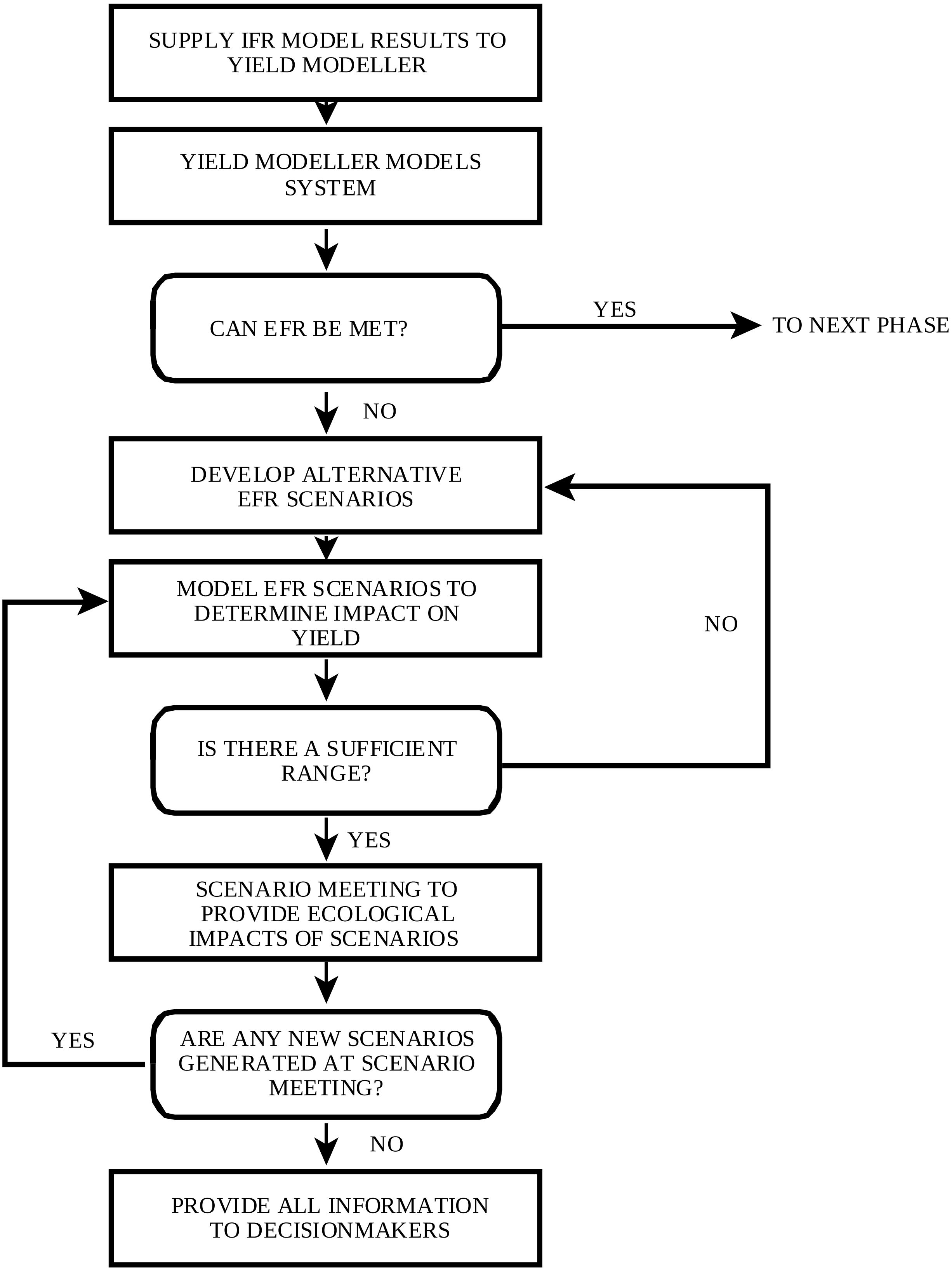


Figure 22.5 Flow diagram illustrating the interactive process during the yield phase.

  - **Original EFR**: Maintenance flows or more occurring 70% of the time. Drought flows 8% of the time.
  - **EFR scenario**: Maintenance flows or more occurring 55% of the time. Drought flows 14% of the time.
- **Hold a Scenario Meeting**. The scenarios are presented to the team, using the surveyed cross-sections to illustrate how each scenario would impact physical habitat and thus the biota. The scenarios are ranked according to their severity of impact on the ecosystem and the EMC.
- **Decide on one scenario**. This is done by the decision maker, based on knowledge of the predicted engineering, financial and social costs, and the ecological implications for river condition.

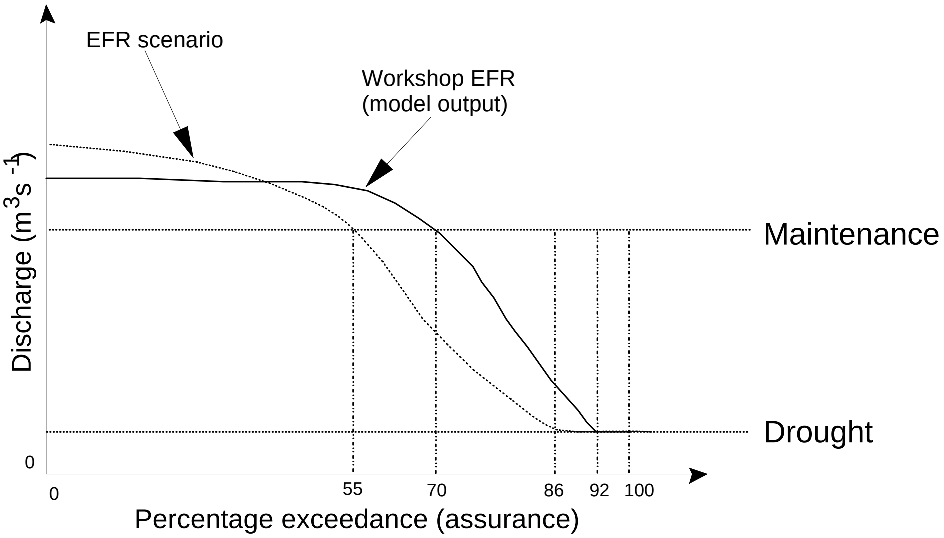


Figure 22.6 Flow duration curve illustrating an example of a workshop result versus a possible scenario.

22.4 DAM DESIGN

Dam design in South Africa has traditionally been undertaken without reference to EFRs. A growing understanding both of the implications of environmental flows for dam design and of the possible negative impacts on the downstream river of a range of design features, is driving the demand for a closer relationship. Recent liaison between dam designers, BBM specialists and dam operation teams, during the planning stages of several South African developments, is leading to a more integrated process. This is still in its infancy, but some issues that are being addressed are outlined below.

Major design features attracting discussion are:

- the size of outlets;
- the need for multi-level outlets;

- tailpond dam versus a plunge pool;
- prior excavation of the plunge pool;
- deforestation of the dam basin;
- the type of dam wall and associated implications.

The main emphasis is usually on the size of outlets required to provide large floods. There are various ways of providing these, for example by using a combination of multi-level outlets and bottom outlets. Each option has cost implications as well as positive and negative environmental effects.

The following sequence of events may occur:

- **Evaluation of design options**: specific design options for supplying the EFR are provided to the BBM team. These are preferably accompanied by photographic examples of the structures, or realistic drawings. The team assesses the nature and severity of the environmental impacts of each option, and flags unacceptable options. Impacts on the immediate downstream river are noted separately from those impacting the greater river system. For any acceptable design options, the underlying expectations of operation are documented.
- **Provision of a dam design scenario(s)**: with this knowledge, a combination of features may be incorporated into one design and, in an iterative process, several different design options presented for consideration by the BBM team. For example, a design scenario could consist of a 100 m concrete dam with two bottom outlets, multi-level outlets at 6-m intervals, and a tailpond dam. An alternative design scenario could be a rockfill dam, with a side-channel concrete spillway that discharges downstream of the dam via an energy dissipator. The options are evaluated in terms of their impacts on the river and effect on the EMC.
- **Identification of preferred option(s)**: the BBM specialists, design engineers and operations team develop a mutual understanding of the implications of each option, and identify preferred options. This evaluation is presented to the decision maker.

22.5 DAM OPERATION

Operation of the dam to supply the EFR is a relatively untested activity in South Africa. The required liaison and actions are being developed for the Injaka Dam project on the Sabie River System, but the dam is not yet in operation. The following proposed process needs testing to ensure that all necessary aspects are addressed.

22.5.1 Linking Environmental Flow Requirement releases to current climate

The use of the IFR Model to simulate design hydrological time series involves calibration using a reference time series that acts as a natural trigger (Hughes *et al.,* 1997). For operational purposes, this natural trigger must be able to be quantified on a near real time basis so that release decisions can be made. Suitable triggers are:

- an upstream gauge that measures reasonably natural flows;
- a gauge in a tributary that measures natural flows and has similar flow characteristics to the river at the BBM sites;
- simulated flow values from a calibrated rainfall model and measured (real time) rainfall data over the catchment.

Establishing a trigger site might require construction of a new gauging weir. For example, the Injaka Dam has been constructed on the Marite River, which is a tributary of the Sabie River. This dam will play a vital role in supplying EFRs for the Sabie River, including the reaches flowing through the Kruger National Park. To guide releases from Injaka, a suitable trigger site on the Sabie River was chosen and a gauge constructed there. Flow information from the gauge will pass to the operator of Injaka Dam, where an operational version of the IFR Model can be used to specify flow requirements for several points along the Sabie. To translate these requirements into actual releases from the dam involves further analyses of the hydraulic routing characteristics of the channels (Section 22.5.2), as well as an allowance for abstractions between the release point and the BBM sites.

Carrying out these analyses for the slowly varying low flow component of the EFR will be relatively straightforward in most cases. However, the definition of trigger rules for flood (or fresh) releases in real time is much more difficult and is likely to involve the use of some form of future forecasting.

With run-of-river abstractions the most appropriate manner of managing the system is by controlling the abstractions rather than determining the required release. Fortunately, such systems are unlikely to require techniques to manage high flows as these largely will be unaffected. However, a trigger site will still be required to indicate when control or restriction of abstractions is required.

22.5.2 Flow releases required to meet the Environmental Flow Requirement

The EFR is described for a number of sites along the river, downstream of the proposed development. Calculating the dam releases that will ensure that the right amount of water arrives at these sites is not a simple task. Flows in rivers are non-uniform and unsteady, and the irregular geometry of natural channels results in complex and strongly non-linear systems along which water flows in intricate patterns. Additionally, abstractions and inflows of water along the river course have to be taken into account. Consequently, it might be necessary to simulate the routing of water through the system, with models such as Mike-11, PROCAN and WAS (Hughes 1999). These hydraulic-routing models are able to estimate flow lag times and evapotranspiration and seepage losses, but they are either very complex and expensive to use, or cannot satisfy all the requirements. The models are also quite data intensive, with the Sabie and Sand river reaches requiring data from approximately 300 cross-sections.

Floods are especially problematic to supply, as the EFR specifies delivery at the BBM site of high flows with a specific discharge and velocity to achieve certain objectives. Complex analyses may be required to ascertain the size of the dam release, and its linkage with natural inflows between the dam and the BBM site, to meet the EFR specifications. Release of substantially higher flows than required at the sites, in order to counteract downstream attenuation of the flood release, could result in negative effects on the river section immediately downstream of the dam. Close liaison should be maintained with the BBM specialists during such activities.

22.6 CONCLUSIONS

Yield analysis is the most developed of the post-workshop phase of the BBM, but all parts of this phase require refining and developing through application in real project developments.

To date, the following issues have become evident:

- close communication and cooperation should be maintained at all stages up to, and beyond, initial operation of the dam, between water managers, engineers, the BBM team of specialists and the design and dam operation specialists;
- tools and processes to aid this liaison need to be developed;
- ecological research is needed to strengthen the present capacity for predicting flow-related changes to rivers; at present ecologists can only provide coarse predictions of change;
- the release of EFRs could have some negative environmental consequences, which should be evaluated, perhaps via EIA or IEM procedures.

It is vital that environmental releases be monitored, to ensure that they adhere to the agreed EFR specifications and achieve the expected objectives. Several protocols for monitoring EFRs have been drafted (e.g. DWAF 1996c; Brown *et al.*, 2000; Metsi 2000b). These can only be refined once a scenario has been decided upon for any one project, as at that point the objectives to be achieved are set and appropriate monitoring can be defined.

Appendix 14.1 Site assessment forms for the geomorphological component of the BBM (see Chapter 14 for further explanation).

SITE GEOMORPHOLOGY
BASELINE STUDY

FORM 1. BASELINE INFORMATION

Recorder		**Date**		**River**	
Site no.		**Altitude**		**Lat.**	
				Long.	

Delete one

Channel gradient **(measured from topographic map scale: 1:50 000 or 1: 10000)________**

FORM 2. CONDITION OF LOCAL CATCHMENT

Rate: none - 0; limited - 1; moderate - 3; extensive - 4; extreme - 5

IMPACT OF:	RATING	COMMENTS
Upstream impoundments		
Interbasin transfer		
Farm dams		
Erosion/gullying		
Land use change		
Water abstraction		
Other		

Appendix 14.1 Continued.

FORM 3. RIPARIAN AND IN-CHANNEL VEGETATION

Rate: none - 0; sparse - 1; patchy - 2; continuous - 3; dense (impenetrable) - 4

DENSITY	**REEDS**	**GRASSES**	**SHRUBS**	**TREES**
macro-channel banks				
top of active channel bank (flood zone)				
active channel banks				
bank toe				
lateral/point bars				
mid-channel bars				

Alien Vegetation

IS THERE INVASIVE ALIEN VEGETATION PRESENT?	

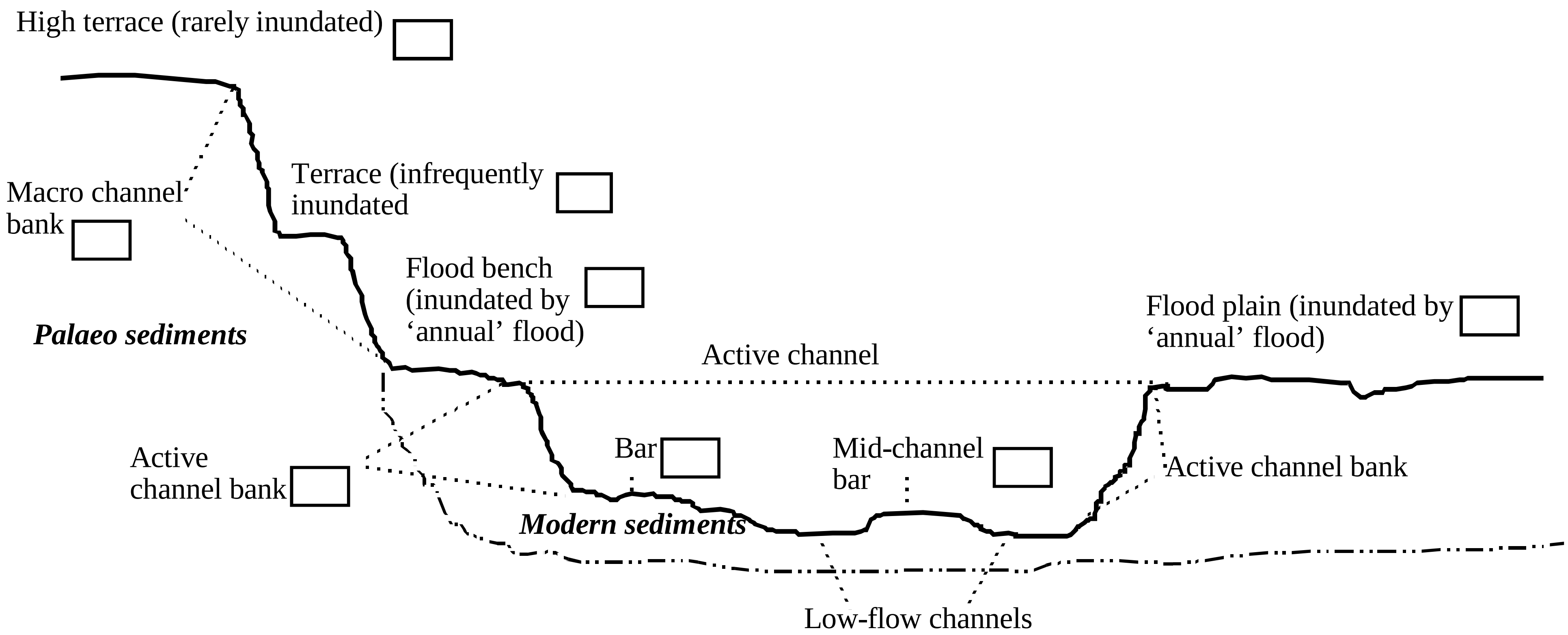
COMMENTS (Note species and specific impacts)

Appendix 14.1 Continued.

FORM 4. CHANNEL PLAN (Insert diagram below)

FORM 5. TEMPLATE FOR CHANNEL CROSS SECTION MORPHOLOGY

Tick box if present:



FORM 5 cont. CHANNEL CROSS SECTIONS

(indicate shape of channel and banks, position and type of vegetation, bank composition, benches, bars, flood levels present water levels, bank full level)

Left hand bank **Right hand bank**
Hydraulic control (specify

Pool

Appendix 14.1 Continued.

FORM 6. SITE GEOMORPHOLOGY

Indicate: Dominant or widespread - D; Localised - L

VALLEY FORM (reach)	
Confined by valley sides - no flood plain	
Moderately confined a) Narrow flood plain, often on one side of channel only	
b) Narrow terrace, entrenched channel	
Unconfined - a) Flood plain	
b) River terraces, entrenched channel	

CHANNEL PATTERN (reach)		
a)	Single thread	
	Anabranching /divided	
b)	Straight/ low sinuosity	
	Meandering - mod. sinuosity	
	Tortuous - v. high sinuosity	
	Wandering	
	Braided	

MORPHOLOGICAL UNITS (site)		
Waterfall		
Rock steps		
Bedrock pavement		
Rapid	Bedrock	
	Boulder	
Bedrock or plunge pool		
Step (cobble or boulder)		
Plain-bed		
Riffle		
Sandwaves (mobile waves of sand)		
Deep pool (alluvial)		
Shallow pool		
Run		
Backwater		

BAR TYPES (site)	
Lateral (formed along side of channel)	
Point (on meander)	
Tributary junction bar (formed at a tributary)	
Lee bar (formed behind an obstruction)	
Mid-channel bar (no or sparse vegetation)	
Braid bar (unstable, no vegetation)	
Island (stable, often vegetated)	
Bedrock core bar (sand or gravel over bedrock, vegetated)	

CHANNEL TYPE (site)
Bedrock
Alluvial
Mixed

REACH TYPE (reach)	
Bedrock fall	
Cascade	
Planar bedrock	
Bedrock rib	
Pool-rapid	
Step-pool	
Plain-bed	
Pool-riffle	
Pool	
Regime	

PERIMETER MATERIAL (site)	**Bank**		**Bed**	
	LHB	**RHB**	**Riffle etc.**	**Pool**
Bedrock				
Boulder				
Cobble				
Mixed (cobble with gravel/sand matrix)				
Gravel				
Sand				
Silt/clay				

Appendix 14.1 Continued.

FORM 7. BED MATERIAL SIZE DISTRIBUTION

Tally occurrences for a sample of 100 randomly selected clasts for each morphological unit

N.B. class limits for clast sizes adapted from Gordon *et al.* (1992), after Brakensiek *et al.* (1979)

	Hydraulic control		**Pool**		**Bar 1**		**Bar 2**	
MORPHOLOGICAL UNIT								
Clast size (mm)	**Tally**	**F**	**Tally**	**F**	**Tally**	**F**	**Tally**	**F**
V. fine sand / silt **<0.125**								
Fine / medium sand **0.125-0.0.5**								
Coarse / v. coarse Sand **0.5-2.0**								
V. fine / fine gravel **2-8**								
Medium gravel **8-16**								
Coarse / v. coarse gravel **16-64**								
Small cobble **64-128**								
Large cobble **128-250**								
Small boulder **250-500**								
Medium boulder **500-1000**								
Large / v. large boulder **1000-4000**								
Bedrock								
Bed packing (X)								
Loosely packed								
Moderately packed								
Tightly packed								

Appendix 14.1 Continued.

FORM 8. PHYSICAL CHARACTERISTICS

Water level at time of sampling

Dry		**Isolated Pool**		**Low Flow**		**Med. Flow**		**High Flow**		**Flood**	

Water turbidity

Clear		**Cloudy**		**Opaque**	

FORM 9. BANK VEGETATION (ACTIVE CHANNEL)

Rate: none - 0; sparse - 1; patchy - 2 continuous - 3; dense (impenetrable) - 4

DENSITY	**Reeds**	**Grasses**	**Shrubs & Trees**
Banks of active channel			

Rate: no impact - 0; limited impact - 2, extensive impact - 3; channel blocked - 4.

COARSE ALIEN WOODY DEBRIS (in channel)	**Amount (Rate 0-5)**	**Source: Local/Upstream**

FORM 10. CHANNEL MODIFICATIONS AND BANK IMPACTS

IN-CHANNEL MODIFICATIONS (Tick if present within 100 m of the study site)		**BANK IMPACTS (at site)** **(Note level of impact)**				
Weir			**none**	**limited**	**moderate**	**severe**
Causeway		**livestock**				
Bridge		**wild animals**				
Fence across river		**footpaths**				
Bulldozing / gravel extraction		**vegetation removal**				
		invasive vegetation				
Gabions		**other**				
Canalisation						
Other						

Appendix 14.1 Continued.

FORM 11. CHANNEL CONDITION

GEOMORPHOLOGICAL INDICATORS

BANK CONDITION

			Tick if present
Active / recent channel incision			
Active - channel shifting			
Macro-channel shifting (cut-offs and avulsion)			
Tick appropriate column		LHB	RHB
A. Fluvial bank erosion (undercutting, slumping, etc. caused by river action) Note % of bank length affected	0%		
	<10%		
	10-33%		
	33-75%		
	>75%		
B. Sub-aerial erosion (sheet wash, rills, etc. on banks not caused by river action): ***tick if present***			
Well-vegetated banks, no sign of erosion			
Sparsely vegetated banks, limited rilling and or livestock tracks			
Steep non-vegetated banks, active rilling and/or gullying and/or extensive livestock trampling			

COMMENTS

BAR CONDITION

Bar types	dominant bar material		width at widest point (% active channel)	encroaching vegetation (0 none - 4 dense) note veg. type	
	sand/ gravel	cobble			
lee					
point					
lateral					
mid-channel					
tributary					

BED CONDITION

Bed material ***(tick the size class of the larger material)***	silt/ clay	sand/ fine gravel	co. gravel/ pebble	cobble/ boulder

Erosion indicators ***tick box if observed***	local (<10% area)	moderate (10-50% area)	extensive (>50% area)
Local bed scour			
Well sorted (uniform) clean gravel/cobble	N.A.	N.A.	
Bedrock pavement			

Deposition indicators ***tick box if observed***	local (<10% area)	moderate (10-50% area)	extensive (>50% area)
Silt deposits in pools (give maximum depth of silt)			
Silt drapes on channel margins / over cobbles or boulders			
Embedded cobbles	limited	moderate	extensive
Riffle, run, plane bed			
Pools			

Tendency towards flat bed of sand or fine gravel	moderate		definite	
Overbank deposition	minor		widespread	

Appendix 14.1 Continued.

FORM 12. GENERAL ASSESSMENT (Circle appropriate rating)

A. Rating table for bank condition

Condition	Rating
Stable: erosion-resistant soils, no undermining, usually gentle slope, good vegetation cover, no significant damage to bank structure or vegetation, no exposed roots	0
Limited erosion: good vegetation cover, some minor isolated erosion, no continuous damage to bank structure or vegetation, some exposed roots	1
Moderate erosion: banks held by discontinuous vegetation, some obvious damage to bank structure and vegetation, generally stable toe, moderately exposed roots, erosion limited to one bank	2
Extensive erosion: little effective vegetation, mostly unstable toe, large numbers of exposed roots	3
Extreme erosion: evidence of rapid unchecked erosion, no effective vegetation, unstable toe, very recent bank movement, erosion on both banks	4

B. Rating table for bed degradation

Condition	Rating
Nil bed degradation: no evidence of degradation	0
Moderate bed degradation: absence of fine alluvial material, narrow low flow course, evidence of recent minor deepening	2
Extreme bed degradation: evidence of recent severe deepening, possible erosion heads	4

C. Rating table for bed aggradation

Condition	Rating
Nil bed aggradation: no evidence of aggradation	0
Moderate bed aggradation: accumulation of material at obstructions, bed tending to flat, same size material on bed and bars, evidence of minor overbank siltation, slight to moderately embedded cobbles, moderate silt in pools	2
Extreme bed aggradation: flat bed, channel largely blocked by sand or gravel bars, overbank siltation evident, severely embedded cobbles, extensive silt in pools	4

rating (zone / channel type / bank / degradation / aggradation)					

FORM 13. HYDRAULIC BIOTOPE ANALYSIS

RIVER ________________________SITE________________________MORPHOLOGICAL UNIT______________________DISCHARGE________________________

OBSERVER ___________________________________DATE ________________ (Record water depth in each box used)

Substratum (diameter in mm)	**Dry**	**No Flow**	**Barely Perceptible Flow**	**Smooth Boundary Turbulent Flow**	**Rippled Flow**	**Surging Flow**	**Undular Standing Waves**	**Standing Waves**	**Chutes**	**Free Falling**
Silt (<0.125)										
Sand (0.125-2)										
Fine gravel (2-16)										
Coarse gravel (16-64)										
Mixed (cobble with gravel, & sand)										
Cobble (64-250)										
Boulder (250-1000)										
V. large boulder or bedrock (>1000)										

Appendix 15.1 Useful web site addresses for the water quality component of the BBM (see also Chapter 15).

Institute for Water Quality Studies (DWAF) – now known as Resource Quality Services Home Page: www.dwaf..gov.za/iwqs/

Water quality database: www.dwaf.gov.za/iwqs/wms

River Health Programme (CSIR): www.csir.co.za/rhp/

Water Research Commission: www.wrc.org.za

Appendix 17.1 Flow-linked characteristics of aquatic invertebrates for use in the BBM (see also Chapter 17).

This appendix details examples of flow-linked characteristics of invertebrates. Some examples are of a general nature and others are more specific; some are taken from the local literature, and others from literature on Northern Hemisphere temperate areas. Individual references have not been quoted, but a useful start would be Ward (1992), King & Tharme (1994) and Skorozewski & De Moor (1999). Some unpublished findings have also been included, notably from F. de Moor of the Albany Museum, Grahamstown.

Appendix 17.1a Trends for particular aquatic invertebrate groups.

AQUATIC INVERTEBRATE GROUP	LINK WITH FLOW
COLEOPTERA	Pupae of some species have spiracular gills which function in water and air, allowing toleration of fluctuating wet-dry conditions.
Elmidae	Some species dig deep into sediments during floods. Most species tolerate stranding during drought periods, by burrowing deep into sediments.
Peloriolus sp.	Preferred water depth 0.2-0.4 m. Preferred velocity from stationary to 0.3 m s^{-1}. Preferred substratum is cobble with a small proportion of sand, but cobble with no sand is acceptable. Bedrock and pure sand are rarely used.
Stenelmis sp.	Larvae migrate up bank during spates, and may be stranded by flood recession. This is their cue to pupate.
COLEOPTERA & HEMIPTERA	Some species avoid floods by flying or swimming out of stream.
DIPTERA	Pupae of some species have spiracular gills, that function in both water and air. They can thus tolerate fluctuating wet-dry conditions.
Chironomidae	Tolerant of up to 120 hours of exposure in cool conditions. Larvae, especially the first instars, migrate upwards when oxygen concentrations drop. Some species tolerate a daily drop in oxygen, but cannot tolerate a prolonged period of low oxygen levels. Tolerate stranding during drought periods, by burrowing deep into sediments. Those species with short life cycles may dominate the invertebrate community in the initial stages of recovery after a flood.
Simuliidae	Larvae drift in velocities that are too slow and too fast for their requirements; this differs between species. Most larvae occur on the upstream face of the upper surface of boulders, where they are subjected to high velocities. They move to downstream faces or crevices to pupate. The feeding fans of blackflies are held open by water current at high velocities and close if the current slows.
Chironomidae, Simuliidae & Tipulidae	Various species are able to survive drought in the egg stage. When egg hatching occurs during the drought, all juveniles may die. Species with drought-resistant eggs may perish if in the aquatic stage during the drought.
DIPTERA SPECIES WITH FLOW-RELATED INFORMATION AVAILABLE	
Lipsothrix sp. (craneflies)	Uses receding water as cue for pupation. Without this cue, larval stage is extended for one year or more.
Polypedilum sp.	Prefer shallow water (0.1-0.2 m), but occur in water up to 0.5 m deep. Found in slow velocities, but higher velocities up to 0.7 m s^{-1} favoured. Favoured substratum sand, but also found in most other substrata.
Rheotanytarsus	Dramatic increase in numbers in drift as discharge increases, followed by rapid decline in numbers even though discharge remains high.

Appendix 17.1a Continued

AQUATIC INVERTEBRATE GROUP	LINK WITH FLOW
Rheotanytarsus cont.	Preferred depth 0.4-0.5 m, but tolerates a wider range of depths. Preferred velocity 0.3-0.9 m s^{-1}, and intolerant of velocities less than this. Sandy bed completely unsuitable; preference for cobble substratum with some sand or sand-free rock.
Simulium	Positive correlation between density and current, irrespective of depth; probably due to food availability.
S. adersi	Widespread species, tolerant of pollution and saline conditions. Usually found in slow-flowing, medium-sized rivers with a stable flow regime.
S. damnosum	Found in swift-flowing sections of rivers, in riffles and on marginal vegetation.
S. metomphallus	Requires swift-flowing conditions (0.8-1.5 m s^{-1}), with clean bedrock or large boulders and cobbles.
S. mcmahoni, S. rotundum & S. cervicornutum	Found in slow to moderately swift flowing water (0.2-1.0 m s^{-1}), distributed sparsely either on stones, dead leaves or vegetation. These three species are often found in shallow-flowing, warm water.
S. virgatum	Repeated flooding allows co-existence with *Hydropsyche oslari* (see Trichoptera). Constant flow favours *Hydropsyche*, which dominate.
Tabanus sp.	Pupae do not have spiracular gills, but still highly tolerant of fluctuating wet-dry conditions.
EPHEMEROPTERA	Susceptible to stranding and intolerant of exposure by, for instance, rapidly receding water levels. The baetids are an exception, as detailed below. Tend to become entangled with filamentous algae. Some mayflies, if unable to satisfy oxygen requirements by gill movements or positioning, emigrate by actively entering the drift. Some species survive drought in the egg stage. When egg hatching occurs during drought, all juveniles may die. Species with drought-resistant eggs are likely to perish if in their aquatic life stage during the drought. Some species may be eliminated from the river by floods, until the next generation.
Baetidae & Ephemerellidae	In the western Cape, baetid numbers naturally decrease with decreasing flow, while Ephemerellidae increase.
Baetidae & Heptageniidae	In high velocities (2-4 m s^{-1}), some species found on upper surface of rocks, some on more sheltered faces and some confined to the underside and areas well protected from current.
Caenidae	Tolerates some silt deposition and slow flows.
Leptophlebiidae	Requires clean water with moderate to fast flows.
Heptageniidae	Requires strong flows of 0.5-1.2 m s^{-1}.
EPHEMEROPTERA SPECIES WITH FLOW-RELATED INFORMATION AVAILABLE:	
Baetis sp.	Avoid stranding by drifting with receding water and crawling towards deeper water. May become trapped in small depressions that then dry out.
Baetis rhodani	Eliminated when flow ceases and water becomes stagnant.
Centroptiloides bifasciata	Occur in the swiftest flowing water, on large boulders and stones.
Demoreptus spp.	Specific in their flow requirements, needing fairly rapid flow and clean water.
Elassoneuria trimeniana	Require strong, perennial flow, in warmer waters than *Oligoneuriopsis lawrencei*.
Ephemerella	Distribution within a riffle inversely correlated with depth and velocity, or no consistent trend.
E. ignita	No immediate increase in numbers in the drift with increasing flow, but nocturnal drift numbers are much elevated.

Appendix 17.1a Continued.

AQUATIC INVERTEBRATE GROUP	LINK WITH FLOW
Heptagenia sulphurea	Populations severely reduced during droughts.
Oligoneuriopsis lawrencei	Occur in swift to torrential flows on large boulders or cobbles, are univoltine and need perennially flowing water. Overwintering diapause eggs, that need cool well-oxygenated water throughout the summer period to complete development.
Potamocloeon macafertiorum	Occur in reaches with slow flow and sandy substrata.
Povilla adusta	Emergence of this lake dwelling African species occurs in response to lunar phase. Emergence may be adversely affected by water turbidity.
Prosopistoma crassi	Inhabit large cobbles to boulders, in flows exceeding 0.8 m s^{-1}.
Pseudopannota maculosa	Occur in the swiftest flowing water, on large boulders and stones.
Rhithrogena	Distribution within a riffle positively correlated with depth and velocity.
Tricorythus	Found in eroding biotopes. Tolerant of moderate pollution and a moderate to swift flow regime, but silt deposits restrict distribution.
Baetis harrisoni, Pseudocloeon glaucum, *P. vinosum*, *Cheleocloeon excisum & Afroptilum sudafricanum*	Widespread and able to survive under a variety of conditions in South Africa.
LEPIDOPTERA	Some aquatic moths survive irregular flows well, because of their constructed shelters on rock surfaces.
ODONATA	
Ophiogomphus severus	Nymphs favoured by low flows, which concentrate prey species and eliminate fish predators.
TRICHOPTERA	Mature larvae move into deep water to pupate. Some species dig deep into sediments during floods.
Cased caddis	Tolerant of exposure and high temperatures.
Hydropsychidae	Positive correlation exists between density and current irrespective of depth, perhaps due to food availability. They have a range of flow requirements and tolerance to silt. Often associated with water rich in phytoplankton.
Hydroptilidae	Require filamentous algae and swift flows.
TRICHOPTERA SPECIES WITH FLOW-RELATED INFORMATION AVAILABLE:	
Cheumatopsyche thomasseti & C. afra	Widespread, tolerant species, needing a strong flow over riffles or rapids to keep stone surfaces cleared of sediment and to support their silken collecting nets. Synchronisation of spring emergences plays an important part in controlling pest blackfly population levels in medium to large rivers (>5 m^3 s^{-1}).
Glossosoma	Inhabit exposed microhabitats, but move to sheltered locations as velocity increases. Pupae found in areas of higher velocity than larvae, perhaps to reduce their chance of stranding if water level drops.
Hydropsyche sp.	Larvae susceptible to stranding, although may survive up to 48 hours in cool conditions, hiding under rocks or algae. Species with nets of large surface area favour slower velocities, while those with nets with streamlined, rigid shapes favour higher velocities. Under unfavourable flows (too low or too high), larvae fail to produce nets. Individuals rapidly move to favourable areas.
H. separata	Favoured by turbid water conditions, and replaced by other species if turbidity decreases.
Leucotrichia sp.	Unable to survive on shallow stones which become exposed, or on stones likely to roll, thus making space for other species with shorter life cycles.

Appendix 17.1b General trends in responses of aquatic invertebrates to flow-related environmental change.

ENVIRONMENTAL VARIABLE	AQUATIC INVERTEBRATE GROUP	RESPONSE TO CHANGE
Change in flow regime	“Pool” and “riffle” species	After a change in the flow regime, so-called “pool” species may find refuge in riffles, but “riffle” species seldom survive in pools.
	Species of harsh intermittent streams	Hydrologic variables and biotic interactions are less important than physiological traits and life history traits.
	Species of flashy perennial streams	Hydrological conditions are more important determinants of community structure than in intermittent streams.
	Species of predictable perennial streams	Biotic interactions are more important determinants of community structure than in the other two stream types listed above.
Floods	Most invertebrate species	Recolonisation takes place within 2-3 months after a severe flood event, but may take years after a catastrophic event. The first flood of the wet season can reduce densities significantly, but ultimately can cause higher biomass afterwards.
Turbidity	All invertebrate species	Moderate increases in turbidity without deposition can reduce macrobenthos of riffles by up to 60%, mostly due to exodus in drift; no mortalities observed. This trend applies uniformly to most taxa. Some species increase in abundance under these conditions.
	Benthic invertebrate populations	Deposition of fine sediments can decimate benthic populations. Sand particles moving along the bottom have a significant impact on benthic species.
	Chironomidae, Ephemeroptera and Oligochaeta	Highly turbid water, caused by well-suspended silt, causes a decrease in abundance of chironomids, an increase in oligochaetes and *Tricorythodes*, but little change in baetid populations.
Illumination and Temperature	Some species	Emergence times are often influenced by both thermal and photoperiod factors. Light becomes more important when thermal conditions are constant.
Temperature	Some species	Warmer temperatures may hasten egg hatching. Eggs hatch sooner under diel temperature cycles than under constant temperature as, for instance, from a dam outlet. Temperature plays an important role in growth and development, with both absolute values and thermal summation affecting different stages of the life cycle.

Appendix 17.1b Continued.

ENVIRONMENTAL VARIABLE	AQUATIC INVERTEBRATE GROUP	RESPONSE TO CHANGE
Oxygen	Lotic species	Most cannot tolerate a drop in oxygen. Some species can adapt morphologically (e.g. by having larger gills) to cope with reduced oxygen. For some (e.g. Plecoptera), high current speeds with low oxygen levels result in fewer mortalities than low current speeds with the same oxygen levels.
Low flow conditions	Simuliidae, Trichoptera and Odonata (damselflies)	Some cannot survive zero current speeds even if oxygen is at saturation level.
	Species in hot climates	In temporary streams in hot climates, more species recolonise as flying adults than via resistant eggs or diapausing larvae. Some caddisflies have been found to survive as larvae.
	Species in cooler climates	In cooler climates, there is a better chance of surviving dry periods as resistant eggs, larvae, or by hiding in the sediment.
	Ephemeroptera, Trichoptera, Plecoptera and Coleoptera	Ephemeroptera survive the dry season mainly as eggs; Trichoptera as pupae; Plecoptera as nymphs; and Coleoptera as adults.
	Rheophilic species and passive filter feeders	Decrease in number with reduced flows.
	Some filter feeders, detritivores and silt-tolerant species	Increase in numbers with reduced flows.
Substratum	Some invertebrate species	Most benthic invertebrates occur in a specific range of substratum types, all of which can be influenced by flow: • Cobble substrata provide diverse microhabitats and support a large diversity of species. • In small forested streams, leaf litter and gravel may support a higher diversity of invertebrates than cobbles. • In some rivers, invertebrate diversity is directly proportional to substratum particle size. Coarser particles only occur in currents. • The standing crop (population size) varies according to substratum type. In one study, the following substrata supported increasingly high standing crops: sand, marl, fine gravel, sand and silt, rubble, *Clara* (a plant), gravel and rubble, moss on gravel, moss on gravel and rubble, and various aquatic plants.
	All insects	• Distribution in a riffle may or may not be dependent on substratum type.

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