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A GLOBAL PERSPECTIVE ON ENVIRONMENTAL FLOW ASSESSMENT: EMERGING TRENDS IN THE DEVELOPMENT AND APPLICATION OF ENVIRONMENTAL FLOW METHODOLOGIES FOR RIVERS

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ABSTRACT

Recognition of the escalating hydrological alteration of rivers on a global scale and resultant environmental degradation, has led to the establishment of the science of environmental flow assessment whereby the quantity and quality of water required for ecosystem conservation and resource protection are determined.

A global review of the present status of environmental flow methodologies revealed the existence of some 207 individual methodologies, recorded for 44 countries within six world regions. These could be differentiated into hydrological, hydraulic rating, habitat simulation and holistic methodologies, with a further two categories representing combination-type and other approaches.

Although historically, the United States has been at the forefront of the development and application of methodologies for prescribing environmental flows, using 37% of the global pool of techniques, parallel initiatives in other parts of the world have increasingly provided the impetus for significant advances in the field.

Application of methodologies is typically at two or more levels. (1) Reconnaissance-level initiatives relying on hydrological methodologies are the largest group (30% of the global total), applied in all world regions. Commonly, a modified Tennant method or arbitrary low flow indices is adopted, but efforts to enhance the ecological relevance and transferability of techniques across different regions and river types are underway. (2) At more comprehensive scales of assessment, two avenues of application of methodologies exist. In developed countries of the northern hemisphere, particularly, the instream flow incremental methodology (IFIM) or other similarly structured approaches are used. As a group, these methodologies are the second most widely applied worldwide, with emphasis on complex, hydrodynamic habitat modelling. The establishment of holistic methodologies as 8% of the global total within a decade, marks an alternative route by which environmental flow assessment has advanced. Such methodologies, several of which are scenario-based, address the flow requirements of the entire riverine ecosystem, based on explicit links between changes in flow regime and the consequences for the biophysical environment. Recent advancements include the consideration of ecosystem-dependent livelihoods and a benchmarking process suitable for evaluating alternative water resource developments at basin scale, in relatively poorly known systems. Although centred in Australia and South Africa, holistic methodologies have stimulated considerable interest elsewhere. They may be especially appropriate in developing world regions, where environmental flow research is in its infancy and water allocations for ecosystems must, for the time being at least, be based on scant data, best professional judgement and risk assessment.

KEY WORDS: environmental flow assessment; environmental flow methodologies; riverine ecosystems; country applications; global trends; developing regions

INTRODUCTION

On a worldwide scale, existing and projected future increases in water demands have resulted in an intensifying, complex conflict between the development of rivers (as well as other freshwater ecosystems) as water and energy sources, and their conservation as biologically diverse, integrated ecosystems (Dynesius and Nilsson, 1994; Abramovitz, 1995; Postel, 1995; McCully, 1996; World Commission on Dams (WCD), 2000; World Conservation Union (IUCN), 2000; Green Cross International (GCI), 2000). A growing field of research dedicated to assessing the requirements of rivers for their own water, to enable satisfactory tradeoffs in water allocation among all users of

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the resource and the resource base itself (the river), has been stimulated by this ongoing conflict. This paper aims to provide a global overview of the current status of development and application of methodologies for addressing the environmental flow needs of riverine ecosystems, against the background of an ever-increasing rate of hydrological alteration of such systems worldwide and the resultant environmental impacts. It outlines the main types of environmental flow methodologies available and explores the extent to which they have been utilized in different countries and world regions, with emphasis on the identification of emerging global trends.

River regulation as a global phenomenon

Over half of the world's accessible surface water is already appropriated by humans, and this is projected to increase to an astounding 70% by 2025 (Postel *et al.*, 1996; Postel, 1998). Water resource developments such as impoundments, diversion weirs, interbasin water transfers, run-of-river abstraction and exploitation of aquifers, for the primary uses of irrigated agriculture, hydropower generation, industry and domestic supply, are responsible worldwide for unprecedented impacts to riverine ecosystems, most of which emanate from alterations to the natural hydrological regime (Rosenberg *et al.*, 2000).

Revenga *et al.* (1998, 2000) estimate that 60% of the world's rivers are fragmented by hydrologic alteration, with 46% of the 106 primary watersheds modified by the presence of at least one large dam. In a study of 225 basins throughout the world, Nilsson *et al.* (2000, cited in Bergkamp *et al.*, 2000) found that 83 (37%) and 54 (24%) of rivers in the basins were highly or moderately fragmented, respectively. Dynesius and Nilsson (1994) calculated that 77% of the total discharge of the 139 largest river systems in North America, Europe and the republics of the former Soviet Union, is strongly or moderately affected by flow-related fragmentation of river channels. Moreover, they observed that large areas in this northern third of the world entirely lack unregulated large rivers. Members of the European Union regulate the flow of 60 to 65% of the rivers in their territories, while in Asia, just under 50% of all rivers that are regulated have more than one dam (WCD, 2000). In the United States alone, over 85% of all inland surface waters are artificially controlled, including by more than 6575 large dams, with only 2% of the region's 5.1×10^6 km of rivers and streams remaining undeveloped and free-flowing (Abramovitz, 1995; Pringle, 2000; WCD, 2000).

Flow regulation through impoundment represents the most prevalent form of hydrological alteration with, according to most recent estimates, currently over 45 000 (and probably far closer to 48 000) large dams in over 140 countries (WCD, 2000); a further 800 000 small dams are estimated to exist worldwide (McCully, 1996). A simplified, summary breakdown of the proportion of large dams by region and by country is given in Figure 1 and Table I, respectively. The top five dam-building countries (Table I) account for close to 80% of all large dams worldwide, with China alone possessing nearly half the world total. Furthermore, approximately two-thirds of the world's extant large dams are located in developing countries (Figure 1; WCD, 2000).

A vast body of scientific research has accumulated supporting a natural flow paradigm (*sensu* Poff *et al.*, 1997), where the flow regime of a river, comprising the five key components of variability, magnitude, frequency, duration, timing and rate of change, is recognized as central to sustaining biodiversity and ecosystem integrity (Poff and Ward, 1989; Karr, 1991; Richter *et al.*, 1997; Rapport *et al.*, 1998; Rosenberg *et al.*, 2000). Detailed discussions of the incontrovertible ecological effects (and knock-on social and economic implications) of hydrological alterations on riverine ecosystems, at globally relevant scales, with impacts ranging from genetic isolation through habitat fragmentation, to declines in biodiversity, floodplain fisheries and ecosystem services, are presented in, for example, Ward and Stanford (1979), Ward (1982), Petts (1984), Lillehammer and Saltviet (1984), Armitage (1995), Cushman (1985), Craig and Kemper (1987), Gore and Petts (1989), Calow and Petts (1992), Boon *et al.* (1992, 2000), Richter *et al.* (1998), Postel (1998), Snaddon *et al.* (1999), Pringle (2000), WCD (2000), Bergkamp *et al.* (2000), and Bunn and Arthington (2002). Numerous regional and/or country-specific discussions of the topic exist, for example: Africa (Davies *et al.*, 1993; Chenje and Johnson, 1996; Acreman *et al.*, 2000); North America (Sparks, 1992, cited in Richter *et al.*, 1997; Contreras and Lozano, 1994; Dynesius and Nilsson, 1994; Pringle *et al.*, 2000); Australia (Walker, 1985; Walker *et al.*, 1995; Kingsford, 2000); tropical Asia (Chen and Wu, 1987, cited in Richter *et al.*, 1997; Dudgeon, 1992, 1995, 2000); Europe and Eurasia (Armitage, 1980; Newson, 1992; Dynesius and Nilsson, 1994); South and Central America (Pringle *et al.*, 2000). Additional, recent treatments of various aspects of river conservation for world regions are presented in Boon *et al.* (2000), as well as

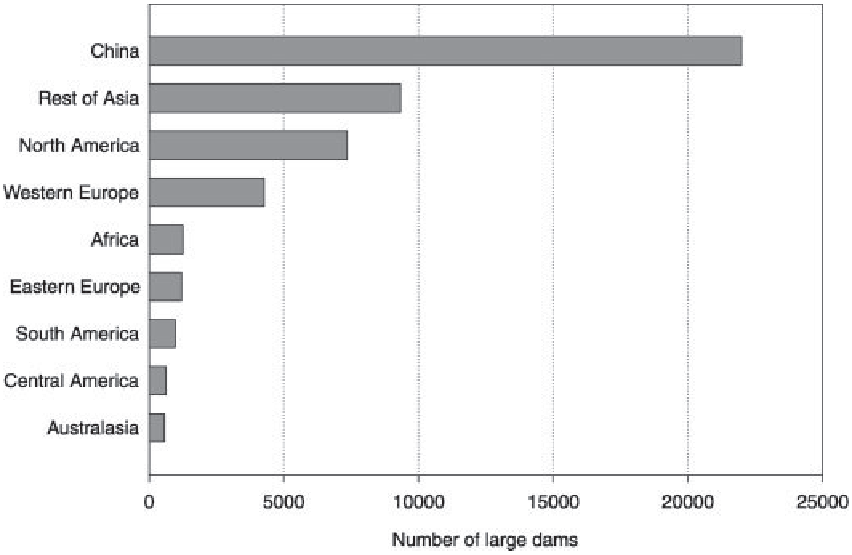

Figure 1. Current regional distribution of large dams (adapted from WCD, 2000). China and Australasia (Australia, New Zealand, Papua New Guinea and Fiji) were treated separately from the rest of Asia, and Central America (including Mexico) from North America (United States and Canada)

Table I. The top 20 countries worldwide by number of large dams (adapted from WCD, 2000)

	Country	ICOLD World Register of Dams 1998	Other sources	Percent of total dams
1	*China	1855	22 000	46.2
2	*United States	6375	6575	13.8
3	*India	4011	4291	9.0
4	*Japan	1077	2675	5.6
5	*Spain	1187	1196	2.5
6	Canada	793	793	1.7
7	South Korea	765	765	1.6
8	Turkey	625	625	1.3
9	Brazil	594	594	1.2
10	France	569	569	1.2
11	South Africa	539	539	1.1
12	Mexico	537	537	1.1
13	Italy	524	524	1.1
14	United Kingdom	517	517	1.1
15	Australia	486	486	1.0
16	Norway	335	335	0.7
17	Germany	311	311	0.7
18	Albania	306	306	0.6
19	Romania	246	246	0.5
20	Zimbabwe	213	213	0.4
	Others	3558	3558	7.0
	Total	**25 423**	**47 655**	**100.0**

*Estimates for the numbers of dams in these countries (particularly China) as well as for the Russian Federation, differ according to available data sources.
ICOLD, International Commission on Large Dams.

in Gopal and Wetzel (1995), and Wetzel and Gopal (1999, 2001), for developing countries. These various sources serve to confirm Abramovitz's (1995) assertion that 'as biological assets, freshwater systems are both disproportionately rich and disproportionately imperiled'.

Evolution of the science of environmental flow assessment

Recognition of the need to establish the extent to which the flow regime of a river can be altered from natural, for the purposes of water resource development and management, while maintaining the integrity (Rapport *et al.*, 1998), or an accepted level of degradation, of the ecosystem has provided the impetus for accelerated development of a relatively new science of environmental flow assessment (Tharme, 1996). An environmental flow assessment (EFA) for a river may be defined simply as an assessment of how much of the original flow regime of a river should continue to flow down it and onto its floodplains in order to maintain specified, valued features of the ecosystem (Tharme and King, 1998; King *et al.*, 1999). An EFA produces one or more descriptions of possible modified hydrological regimes for the river, the environmental flow requirements (EFRs), each linked to a predetermined objective in terms of the ecosystem's future condition. For instance, these objectives may be directed at the maintenance or enhancement of the entire riverine ecosystem, including its various aquatic and riparian biota and components from source to sea, at maximizing the production of commercial fish species, at conserving particular endangered species, or protecting features of scientific, cultural or recreational value.

Typically, EFAs are performed for river systems that are already regulated or are the focus of proposed water resource developments, but more recently, attention has also been directed at the flow-related aspects of river restoration (e.g. Arthington *et al.*, 2000). The resultant EFR may be specified at several levels of resolution, from a single annual flow volume through to, more commonly nowadays, a comprehensive, modified flow regime where the overall volume of water allocated for environmental purposes is a combination of different monthly and event-based (e.g. low flows and flood pulses) allocations. The scale at which the EFA is undertaken may also vary widely, from a whole catchment for a large river basin that includes regulated and unregulated tributaries, to a flow restoration project for a single river reach (King *et al.*, 1999). Different methodologies are appropriate over such a broad range in spatial scale and resolution, as well as in accordance with constraints including the time frame for assessment, the availability of data, technical capacity and finances (Tharme, 1996; Arthington *et al.*, 1998a). They range from relatively simplistic, reconnaissance-level approaches for the early phases of country-wide, water resource planning initiatives, to resource intensive methodologies for highly utilized, individual catchments or sites.

Concerted development of methodologies for prescribing EFRs began at the end of the 1940s, in the western United States of America. Dramatic progress was achieved during the 1970s, primarily as a result of new environmental and freshwater legislation and demands from the water planning community for quantitative documentation of EFRs (Stalnaker, 1982; Trihey and Stalnaker, 1985), in concert with the peak of the dam-building era (WCD, 2000). Outside the United States, the route by which environmental flow methodologies (EFMs) became established for use is less well documented (Tharme, 1996). In many countries, the process only gained significant ground in the 1980s (e.g. Australia, England, New Zealand and South Africa) or later (e.g. Brazil, Czech Republic, Japan and Portugal). Other parts of the world, including eastern Europe, and much of Latin America, Africa and Asia, appear poorly advanced in the field, with little published literature that deals specifically with environmental flow issues.

Types of environmental flow methodologies

A vast body of formal methodologies now exists for addressing EFRs, which has been reviewed over time, including Stalnaker and Arnette (1976), Wesche and Rechard (1980), Morhardt (1986), Estes and Orsborn (1986), Loar *et al.* (1986), Kinhill Engineers (1988), Reiser *et al.* (1989a), Arthington and Pusey (1993), Growns and Kotlash (1994), Karim *et al.* (1995), Tharme (1996, 1997, 2000), Jowett (1997), Stewardson and Gippel (1997), Dunbar *et al.* (1998), Arthington (1998a), Arthington and Zalucki (1998a,b), Arthington *et al.* (1998a,b) and King *et al.* (1999).

The majority of EFMs described can be grouped into four (of six) reasonably distinct categories, namely hydrological, hydraulic rating, habitat simulation (or rating), and holistic methodologies, although differences in group classifications do occur among authors (Loar *et al.*, 1986; Gordon *et al.*, 1992; Swales and Harris, 1995; Tharme, 1996; Jowett, 1997; Dunbar *et al.*, 1998). These four methodology types comprise the focus of this paper.

The simplest, typically desktop EFMs, hydrological methodologies, rely primarily on the use of hydrological data, usually in the form of naturalized, historical monthly or daily flow records, for making environmental flow recommendations. They are often referred to as fixed-percentage or look-up table methodologies, where a set proportion of flow, often termed the minimum flow (Cavendish and Duncan, 1986; Milhous *et al.*, 1989), represents the EFR intended to maintain the freshwater fishery, other highlighted ecological features, or river health at some acceptable level, usually on an annual, seasonal or monthly basis. Occasionally, hydrology-based EFMs include catchment variables (e.g. O'Shea, 1995), are modified to take account of hydraulic, biological and/or geomorphological criteria (e.g. Estes, 1996), or incorporate various hydrological formulae or indices (e.g. Ubertini *et al.*, 1996). Gordon *et al.* (1992), Stewardson and Gippel (1997) and Smakhtin (2001) review many of the well established hydrological and regionalization techniques used to derive the latter flow indices for gauged and ungauged catchments. As a result of their rapid, non-resource-intensive, but low resolution environmental flow estimates, hydrological methodologies are considered to be most appropriate at the planning level of water resource development, or in low controversy situations where they may be used as preliminary flow targets (Tharme, 1997; Dunbar *et al.*, 1998).

From the 1970s onwards, initially in North America and alongside hydrological EFMs, there was rapid development of methodologies that utilized a quantifiable relationship between the quantity and quality of an instream resource, such as fishery habitat, and discharge, to calculate EFRs (e.g. Stalnaker and Arnette, 1976; Prewitt and Carlson, 1980). These examined, for the first time, the effects of specific increments in discharge on instream habitat, with most emphasis placed on the passage, spawning, rearing and other flow-related maintenance requirements of individual, economically or recreationally important fish species (Tharme, 1996). Pioneers of this approach included Collings *et al.* (1972, cited in Trihey and Stalnaker, 1985) and Waters (1976). Two groups of transect-based methodologies evolved from these foundations, hydraulic rating and habitat rating EFMs (Stalnaker, 1979; Trihey and Stalnaker, 1985).

Loar *et al.* (1986) coined the term 'hydraulic rating' (also known as habitat retention) methodologies for approaches that use changes in simple hydraulic variables, such as wetted perimeter or maximum depth, usually measured across single, limiting river cross-sections (e.g. riffles), as a surrogate for habitat factors known or assumed to be limiting to target biota. The implicit assumption is that ensuring some threshold value of the selected hydraulic parameter at altered flows will maintain the biota and/or ecosystem integrity. Environmental flows are calculated by plotting the variable of concern against discharge. Commonly, a breakpoint, interpreted as a threshold below which habitat quality becomes significantly degraded, is identified on the response curve, or the minimum EFR is set as the discharge producing a fixed percentage reduction in habitat.

Tharme (1996) and Dunbar *et al.* (1998) consider these methodologies to be the precursors of more sophisticated habitat rating or simulation methodologies, also referred to as microhabitat or habitat modelling methodologies. These techniques attempt to assess EFRs on the basis of detailed analyses of the quantity and suitability of instream physical habitat available to target species or assemblages under different discharges (or flow regimes), on the basis of integrated hydrological, hydraulic and biological response data. Typically, the flow-related changes in physical microhabitat are modelled in various hydraulic programs, using data on one or more hydraulic variables, most commonly depth, velocity, substratum composition, cover and, more recently, complex hydraulic indices (e.g. benthic shear stress), collected at multiple cross-sections within the river study reach. The simulated available habitat conditions are linked with information on the range of preferred to unsuitable microhabitat conditions for target species, lifestages, assemblages and/or activities, often depicted using seasonally defined habitat suitability index curves. The resultant outputs, usually in the form of habitat–discharge curves for the biota, or extended as habitat time and exceedence series, are used to predict optimum flows as EFRs.

Early reviewers recognized only the above three methodology types, while the emergence of a fourth type, 'holistic methodologies', was first documented by Tharme (1996), and is explicitly considered in most subsequent reviews, including those by Stewardson and Gippel (1997), Arthington (1998a) and King *et al.* (1999).

A holistic, ecosystems approach to river management, and specifically EFAs, has been advocated by freshwater ecologists for well over a decade (Ward and Stanford, 1987; Petts, 1989; Hill *et al.*, 1991) and, more recently, has been heralded as one of the chief directions of evolution of the science (Arthington *et al.*, 1992; King and Tharme, 1994; Richter *et al.*, 1996; Dunbar *et al.*, 1998). Indeed, Arthington (1998a) states that from a global perspective, there does not appear to be 'any competing paradigm for environmental flow assessment and management within the context of sustaining water-dependent environmental systems'.

Holistic methodologies emerged from a common conceptual origin (Arthington *et al.*, 1992) to form a distinct group of EFMs focused from the outset towards addressing the EFRs of the entire riverine ecosystem. They rapidly took precedence over habitat simulation EFMs in South Africa and Australia, countries that lack the high profile freshwater fisheries characteristic of North America and where the emphasis is on ensuring the protection of entire rivers and their often poorly known biota.

In a holistic methodology, important and/or critical flow events are identified in terms of select criteria defining flow variability, for some or all major components or attributes of the riverine ecosystem. This is done either through a bottom-up or, more common recently, a top-down or combination process that requires considerable multidisciplinary expertise and input (Tharme 1996, 2000; Tharme and King, 1998; Arthington, 1998a). The basis of most approaches is the systematic construction of a modified flow regime from scratch (i.e. bottom-up), on a month-by-month (or more frequent) and element-by-element basis, where each element represents a well defined feature of the flow regime intended to achieve particular ecological, geomorphological, water quality, social or other objectives in the modified system (King and Tharme, 1994; Arthington, 1998a; Arthington and Lloyd, 1998; Arthington *et al.*, 2000). In contrast, in top-down, generally scenario-based approaches, environmental flows are defined in terms of acceptable degrees of departure from the natural (or other reference) flow regime, rendering them less susceptible to any omission of critical flow characteristics or processes than their bottom-up counterparts (Bunn, 1998).

The most advanced holistic methodologies routinely utilize several of the tools for hydrological, hydraulic and physical habitat analysis featured in the three types of EFM previously discussed, within a modular framework, for establishing the EFRs of the riverine ecosystem (Tharme, 2000). Importantly, they also tend to be reliant on quantitative flow-ecology models as input, especially if they are to possess the predictive capabilities required in EFAs nowadays (Tharme and King, 1998; Arthington *et al.*, 1998b; Dunbar and Acreman, 2001; Bunn and Arthington, in press).

Tharme (1996) and Dunbar *et al.* (1998) recognize a diverse array of methodologies that bear characteristics of more than one of the above four basic types, including partially holistic EFMs which incorporate holistic elements, but within insufficiently developed methodological frameworks. These methodologies are classed as 'combination' (or hybrid) approaches for the purposes of this paper, alongside various other techniques not designed for EFAs from first principles, but adapted or with potential to be used for this purpose. These latter approaches are termed 'other' EFMs. Methodologies from both groups have been categorized by Dunbar *et al.* (1998) as 'multivariate statistical' techniques (a somewhat incomplete definition for this assemblage of disparate methods and analytical techniques).

In addition to these six types of methodologies, and often housed within holistic EFMs, are approaches that have diverged from an emphasis on the relationship between instream habitat, biota and flow, to explore other information best suited to specific river components or other connected ecosystems. Recent (for the most part) reviews, discussion documents or detailed examples are available for wetlands and lakes (McCosker, 1998; DWAF, 1999a), estuaries and the nearshore coastal environment (Bunn *et al.*, 1998; Loneragan and Bunn, 1999; DWAF, 1999b), water quality (Dortch and Martin, 1989; Tharme, 1996; Malan and Day, 2002), geomorphology and sedimentology (Reiser *et al.*, 1987, 1989b; Tharme, 1996; Stewardson and Gippel, 1997; Brizga, 1998), riparian and aquatic vegetation (Tharme, 1996; McCosker, 1998; Mackay and Thompson, 2000; Werren and Arthington, 2003), aquatic invertebrates (Tharme, 1996; Growns, 1998), fish (Tharme, 1996; Pusey, 1998; Kennard *et al.*, 2000), water-dependent vertebrates other than fish (Kadlec, 1976; Tharme, 1996; Zalucki and Arthington, 2000), groundwater-dependent ecosystems (Kite *et al.*, 1994; Hatton and Evans, 1998; DWAF, 1999c; Petts *et al.*, 1999; Parsons and MacKay, 2000; Kirk and Soley, 2000), social dependence (Acreman *et al.*, 2000; Pollard, 2000), and recreation, aesthetics and cultural amenity (Mosley, 1983; Whittaker *et al.*, 1993).

APPROACH

To date, there have been few assessments of either the numbers of individual methodologies of various types utilized for EFAs in individual countries or across world regions, or of their relative frequency of application. This paper addresses only the former subject in any detail, as published information on the numbers of applications per methodology is presently inadequate for the majority of countries. An exception is North America, for which Reiser *et al.* (1989a) reported the most commonly applied EFMs, based on the results of two non-statistical surveys by the American Fisheries Society in the 1980s, and Armour and Taylor (1991) presented an evaluation of the status of the instream flow incremental methodology (IFIM), as the most commonly applied EFM.

The emphasis in this paper is on riverine ecosystems (including their floodplains and connected wetlands). The intention here is not to provide a definitive examination of the character, strengths, deficiences or case applications of specific methodologies, as such information is readily available in the above-mentioned literature reviews. Moreover, Tharme (1996), Jowett (1997) and King *et al*. (1999) provide summary tables describing the main types of EFMs.

Data for the analysis of global trends in river EFMs were derived from the preliminary findings of an international review of available information, from the inception of the field of EFAs to February 2002. Although some information obtained after this time (notably at the March 2002 International Conference on Environmental Flows for River Systems, incorporating the Fourth International Ecohydraulics Symposium, Cape Town, South Africa) has been included here in a tabulated summary, it did not form part of the analysis. The paper is restricted in its coverage of the international situation by the extent to which appropriate literature exists and was accessible, and to which it was possible to establish direct contact informally with overseas researchers. It is acknowledged that a more comprehensive survey is likely to indicate other countries for which new or additional information is available. This is particularly pertinent as the field is rapidly expanding, with the establishment and application of EFMs strongly tied to ever-intensifying regional plans for water resource development, in addition to ongoing policy and legislative reforms. Also in this regard, several known sources of information were not accessible at the time of compilation of this paper.

For each country for which information was available, methodologies that have been developed and/or applied locally were assigned to one of the six types described above. This included EFMs that have been used historically, but appear to have been replaced by other approaches in recent years. Methodologies proposed for future use and/or where no evidence of their actual application could be found, were listed but not included in analyses. Occasionally, information obtained from literature sources was general rather than specific in nature with, for example, reference made to the use of ‘various hydrological indices’, or generic approaches such as multiple transect analysis (MTA) and flow duration curve (FDC) analysis. Such cases were included, but treated singly. In many instances, professional judgement was used alone or in conjunction with an established methodology, for recommending environmental flows. In only the former case was its use counted as an independent approach. Where approaches could not be assigned readily to a methodology type, most often due to poor documentation in the mainstream literature, they were noted under the category, ‘other’. In cases where the developers or users of a particular methodology did not designate it a name, an appropriate one has been assigned for ease of reference. Although results are based simply on numbers of different methodologies and not on frequencies of application, where there was clear evidence of preferential use of an EFM this has been highlighted.

For regional-scale analysis, countries were grouped according to geo-political affinities, with consideration of the amount of information available within each region. Therefore, the number of countries (several of which are further divided into states) per region is variable. Other potential sources of bias include the disproportionately large volume of documented information on environmental flow issues in North America in contrast with the rest of the world, and the fact that most available in-depth reviews of the topic have been written by researchers in North America, Australia, South Africa, England and New Zealand.

RESULTS AND DISCUSSION

Although not fully comprehensive, Appendix I provides a synopsis of the numbers of individual environmental flow methodologies for rivers, by type, that have been and/or are being applied in various countries around the world.

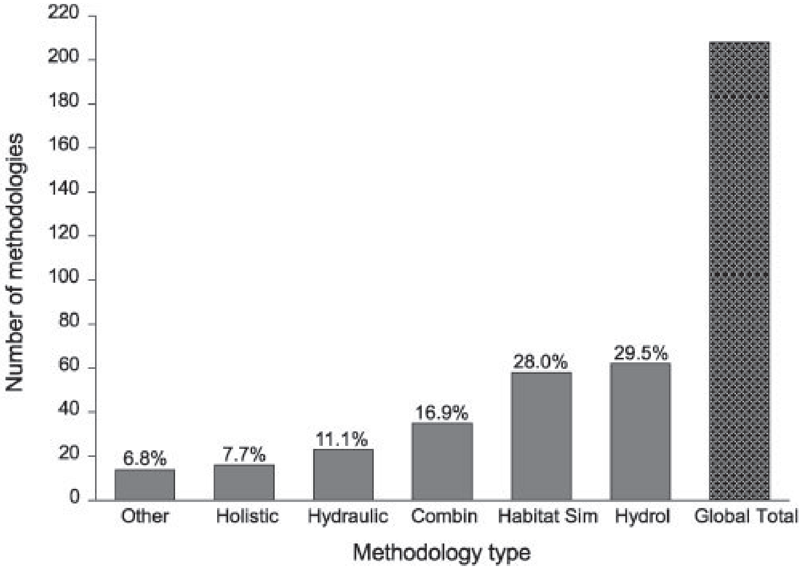

Figure 2. Number of environmental flow methodologies of each type in use worldwide and their relative proportions, compared with the global total. Hydraulic, hydraulic rating; Combin, combination; Habitat Sim, habitat simulation; Hydrol, Hydrological. Methodology types as discussed in the text

Global trends in types of environmental flow methodologies

At least 207 individual methodologies, within the six main types identified above, were recorded in use for 44 countries, within six broad world regions (Appendix I and Figure 2). Actual implementation of methodologies was apparent for all except seven of the total of 51 countries listed. However, interest in a range of specified methodologies was clearly demonstrated in the latter set of countries, which included Cambodia, Tanzania and Mozambique, where environmental flow research is in its infancy. It is highly probable that several other countries not listed in Appendix I, are also currently in the early stages of proposing or applying EFMs for riverine ecosystems.

Hydrological methodologies

Hydrology-based EFMs constituted the highest proportion of the overall number of methodologies recorded (30%, followed closely by habitat simulation EFMs), with a total of 61 different hydrological indices or techniques applied to date (Figure 2). Of these, few (four) appear to have become obsolete over time, and the vast majority remain in use today, either in their original form, or with some degree of modification to improve transferability among different hydrological regions and river ecotypes.

Reiser *et al*. (1989a) highlighted the Tennant (Montana) method as the second most widely used EFM in North America, at that stage used routinely in 16 states or provinces. Since then, it has become the most commonly applied hydrological methodology worldwide. Although superficially a standard-setting approach, the method, developed in the United States by Tennant (1976) and the US Fish and Wildlife Service, differs from many other hydrological methodologies in that considerable collection of field habitat, hydraulic and biological data was involved in its development. It comprises a table linking different percentages of average or mean annual flow (AAF/MAF) to different categories of river condition, on a seasonal basis, as the recommended minimum flows. The categories of flow-related condition range from ‘poor or minimum’ (10% AAF) to ‘optimum range’ (60–100% AAF) (Tennant, 1976). At least 25 countries have either applied the method as originally expounded by Tennant (1976), in a modified form on the basis of various hydrological, geomorphological, ecological or catchment-based criteria (e.g. Tessman and Bayha modifications, Dunbar *et al*., 1998), or have simply utilized various (often arbitrarily designated) percentages or ranges of AAF (Appendix I). Several forms of the basic approach exist in North America particularly, and Estes (1996) provides an example of a modification of the method for use in Alaska, with the addition of specialist knowledge of fish ecology, flow duration estimates, and a mean monthly flow index.

Examples of the use of specific percentages of MAF to set environmental flows include 10% MAF in Spain, for river catchments for which limited information is available (Docampo and De Bikuña, 1993), and routine application of 2.5–5% MAF in Portugal (Alves and Henriques, 1994).

Various exceedence percentiles (or even proportions thereof) derived from analysis of flow duration curves, which display the relationship between discharge and the percentage of time that it is equalled or exceeded (Gordon *et al.*, 1992), and other single flow indices comprise the second largest subgroup of hydrological approaches applied globally, in some 18 countries (Appendix I). Common percentiles and indices recorded in several countries, most often used as minimum flow recommendations, include: Q_{95}, frequently applied, often at a seasonal level, in the United Kingdom (UK), as well as in Bulgaria, Taiwan and Australia; Q_{90}, in Brazil, Canada, and the UK; 7Q10 (consecutive 7-day low flow event with a 1:10 year return period) applied across Brazil at a statewide level (A. Benetti, Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul, Brazil, personal communication), as well as in North America and Italy; and the Q_{364} (natural discharge exceeded for 364 days of the year) and similar indices used throughout Europe.

Since the early 1990s, several EFMs based on hydrological indices that more adequately address flow variability and/or are purported to be more ecologically relevant, have evolved. Such methodologies include the Texas method (Matthews and Bao, 1991) and basic flow method (Palau and Alcazar, 1996), used in at least four and two countries, respectively (Appendix I), as well as the range of variability approach (RVA; Richter *et al.*, 1996, 1997) and flow translucency approach (Gippel, 2001).

Of these approaches, RVA, primarily its component indicators of hydrologic alteration (IHA) software, has been applied most intensively since its inception, in more than 30 environmental flow-related studies in the United States of America (USA) and Canada (B. D. Richter, unpublished document, 2001), as well as in South Africa (G. P. W. Jewitt pers. comm.; V. Taylor pers. comm.). It has also attracted international interest in at least three other countries, is used as a research tool in Australia (A. Arthington, pers. comm.), and merits further investigation according to Tharme (1997), Dunbar *et al.* (1998) and Arthington (1998a).

The RVA aims to provide a comprehensive statistical characterization of ecologically relevant features of a flow regime, where 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 IHAs, are grouped into five categories based on regime characteristics with flow management targets, set as ranges of variation in each index, which can be monitored and refined over time (Richter *et al.*, 1996). In the majority of cases the methodology has been used in trend analysis of pre- and post-regulation scenarios, to characterize the flow-related changes experienced by regulated rivers. However, in several instances, such changes have been correlated with ecological factors (e.g. fish populations, vegetation, water quality, geomorphological processes and species habitat), or have been used to supplement the results of physical microhabitat modelling (Normandeau Associates, pers. comm.). It is noteworthy that several researchers consider RVA an holistic (Arthington, 1998a) or ecologically grounded (Bragg *et al.*, 1999) approach. However, this author suggests that further demonstration of the ecological relevance of the indices should be one of the required steps in this direction.

In another recent hydrological approach that originated in Australia, also based on the tenets of the natural flow paradigm (Poff *et al.*, 1997), and here referred to as the flow translucency approach, the natural flow regime is scaled down in magnitude (using various functions) whilst maintaining similar levels of flow variability, to produce a recommended regulated flow regime (Gippel, 2001). Although showing value, more adequate incorporation of ecological and geomorphological considerations into the methodology is required, according to Gippel (2001).

Hydraulic rating methodologies

Of the 23 hydraulic rating methodologies reported (Appendix I), representing roughly 11% of the global total, most were developed to recommend instream flows for economically important salmonid fisheries in the USA during the 1960s to 1970s (Stalnaker and Arnette, 1976; Tharme, 1996) and have been superseded by more sophisticated habitat simulation EFMs in recent years (or absorbed within holistic EFMs).

The most commonly applied hydraulic rating methodology worldwide today, and already the third most used methodology in North America more than a decade ago (Reiser *et al.*, 1989a), is the generic wetted perimeter method. In the method it is firstly assumed that river integrity can be directly related to the quantity of wetted perimeter, typically in riffles or other critically limiting biotopes, and secondly that preservation of such areas will ensure adequate habitat protection overall. An established empirical or hydraulically modelled relationship between wetted perimeter and discharge is used to determine minimum or preservation flows, usually for fish rearing or maximum production by benthic invertebrates (e.g. Nelson, 1980; Richardson, 1986; Gippel and Stewardson, 1998). The EFR is generally identified from discharges near the curve breakpoint, which is presumed to represent the optimal flow, and below which habitat is rapidly lost (Stalnaker *et al.*, 1994; Gippel and Stewardson, 1996, 1998; Espegren, 1998), or using arbitrary percentages, such as 50% of optimum habitat. A recent detailed application and evaluation of the method is provided in Gippel and Stewardson (1998), for Australia, and it is also used in Europe and most commonly, the USA.

The R-2 cross method also remains in use today, despite being developed in its basic form more than 25 years ago (Anon, 1974, cited in Stalnaker and Arnette, 1976; Nehring, 1979; Espegren, 1998). However, its application is far more localized than the wetted perimeter method, in Colorado, USA, where it is the standard, state-wide method for assessing environmental flows for the region's coldwater rivers (Espegren and Merriman, 1995, cited in Dunbar *et al.*, 1998; Espegren, 1998). As with several other hydraulic rating approaches (Bovee and Milhous, 1978; Tharme, 1996), the method relies on a hydraulic model, R-2 cross, to generate relationships between flow and instream hydraulics, from which EFRs (for fish) are derived using critical hydraulic parameters and expert opinion.

The results presented in Appendix I suggest that there are few recent advances in hydraulic rating methodologies *per se*. Rather, they seem to have fulfilled key roles both in stimulating the development of the more advanced group of habitat simulation EFMs and as tools within holistic methodologies. Additionally, although it is possible that hydraulic rating EFMs will continue to be applied in future, they will likely feature far less prominently than other methodologies.

Habitat simulation methodologies

Habitat simulation methodologies ranked second only to hydrological EFMs at a global scale (28% of the overall total), with approximately 58 recorded from countries throughout the world (Appendix I). Of this number, however, roughly half represent *ad hoc* habitat rating approaches used only a few times historically, within the United States, such as the Idaho method (White, 1976, cited in Stalnaker and Arnette, 1976). Most importantly, a subset of complex EFMs representing the current state of the art, has developed gradually from the earlier, simpler techniques described above. This subgroup includes IFIM (including its cornerstone, the physical habitat simulation model, PHABSIM; Bovee, 1982; Milhous *et al.*, 1989; Nestler *et al.*, 1989; Stalnaker *et al.*, 1994; Milhous, 1998a), and a more recently established suite of habitat simulation models of similar character and data requirements.

The IFIM, initially devised by the then Co-operative Instream Flow Service Group of the US Fish and Wildlife Service (USFWS), Colorado, in the late 1970s (Reiser *et al.*, 1989a), has been considered by some environmental flow practitioners as the most scientifically and legally defensible methodology available for assessing EFRs (Shirvell, 1986; Gore and Nestler, 1988; Dunbar *et al.*, 1998). In essence, it comprises a vast array of hydraulic and habitat simulation models, now housed in a Windows environment (Milhous *et al.*, 1989; Stalnaker *et al.*, 1994; Milhous, 1998a; Stalnaker, 1998; USGS, 2000), that integrate flow-related changes in habitat (as weighted usable area, WUA), with the preferred hydraulic habitat conditions for target species or assemblages. The resultant outputs, often depicted as effective habitat time series and duration curves, are used for recommending EFRs and evaluating alternative flow regulation scenarios (Waddle, 1998a,b). Most often, IFIM has addressed the EFRs of target fish, and to a lesser extent, invertebrate species (e.g. Orth and Maughan, 1982; Gore, 1987; King and Tharme, 1994; Stalnaker *et al.*, 1996), but in recent years, it has been adapted for a variety of other ecosystem components and situations (Tharme, 2000). For instance, Milhous (1998b) reports on the use of IFIM for an assessment of flows for sediment flushing, while Gustard and Elliott (1998) provide examples of its application in UK river restoration projects.

Reiser *et al.* (1989a) showed IFIM to be the most commonly used EFM in North America, applied in 38 states or provinces by the late 1980s, and the preferred methodology in 24 cases. Furthermore, a total of 616 IFIM applications, specifically by USFWS offices, was reported in 1988 (Armour and Taylor, 1991). The use of IFIM has accelerated tremendously since then, judging by the plethora of published case studies (Stalnaker, 1998), probably in part due to its long existence, the ready availability of the component software and well-developed training courses. The reader is referred to the recent applications of IFIM listed in Appendix I for various countries, including, among others, studies in Portugal, Japan (Tamai *et al.*, 1996; Nakamura, 1999), the Czech Republic (Blažková *et al.*, 1998), and UK (Gustard and Cole, 1998; Gustard and Elliott, 1998).

It is, therefore, unsurprising that IFIM far exceeds the other methodologies of its type in use worldwide to date, with confirmed use in 20 countries, probable application in at least a further three, and some three countries using the commercially available equivalent, the riverine habitat simulation program (RHABSIM; Payne and Associates, 2000). This trend is in spite of the extensive body of criticism levelled at IFIM over the years, dealing with issues such as the validity of the methodology's base assumptions, the construction and degree of transferability of habitat suitability curves, implementation of the macrohabitat component, the nature of the WUA–discharge output, and the methodology's lack of ecological predictive capability (Mathur *et al.*, 1985; Shirvell, 1986; Scott and Shirvell, 1987; Gan and McMahon, 1990; Arthington and Pusey, 1993; King and Tharme, 1994; Tharme, 1996; Jowett, 1997; Arthington and Zalucki, 1998a).

After IFIM, the computer aided simulation model for instream flow requirements in regulated streams (CASIMIR; Jorde, 1996; Jorde and Bratrich, 1998; Jorde *et al.*, 2000, 2001), first used to model relationships between temporal and spatial patterns in river bottom shear stress and changes in discharge, linked to habitat suitability curves for invertebrates, was reported in use for six countries, all but one in Europe. The Norwegian river system simulator (RSS), comprising hydrological, hydraulic and habitat simulation models for application to rivers regulated by hydropower schemes (e.g. Alfredsen, 1998), and the French evaluation of habitat method (EVHA; Ginot, 1995, cited in Dunbar *et al.*, 1998) also have been used in a few European countries. Other similarly advanced EFMs presently in use globally include: the New Zealand river hydraulics and habitat simulation program (RHYHABSIM; Jowett, 1989; Jowett and Richardson, 1995); the Canadian microhabitat modelling system, HABIOSIM (Dunbar *et al.*, 1998); and the riverine community habitat assessment and restoration concept (RCHARC; Nestler *et al.*, 1996).

The most apparent trends common to several EFMs within this methodology type are a move towards increasingly advanced hydraulic and habitat modelling, at two- and three-dimensional levels of resolution (Hardy, 1996; Ghanem *et al.*, 1996; Blažková *et al.*, 1998; Crowder and Diplas, 2000), the inclusion of complex, spatially explicit habitat metrics, and the use of geographical information system (GIS)-based spatial display platforms (Waddle, 1998b).

Holistic methodologies

Although currently representing only 7.7% of the global total (Figure 2), with in the order of 16 methodologies (listed under Australia, South Africa and the UK in Appendix I), holistic EFMs have contributed greatly to the field of environmental flow assessment in recent years. A synopsis of this broad suite of methodologies is provided in Appendix II, focusing on approaches that are well established and/or present recent advances. Astonishingly, the building block methodology (BBM) remains one of only two EFMs in the world for which a manual has been written (King *et al.*, 2000), the other being IFIM (Milhous *et al.*, 1989).

The origins of perhaps the first holistic EFM to be formalized, the South African BBM (King and Tharme, 1994; Tharme and King, 1998; King and Louw, 1998), can be traced to two early EFA workshops documented in King and O'Keeffe (1989) and Bruwer (1991). Development of the basic approach progressed further through collaboration with Australian researchers, resulting in the establishment of a conceptual framework in 1991, the holistic approach (Arthington *et al.*, 1992). Significantly, the BBM and holistic approach (see Arthington 1998a), which subsequently advanced in parallel in South Africa and Australia, respectively, have provided much of the impetus for the rapid establishment within only a decade of most other methodologies of this type (Tharme, 1996).

The BBM is presently the most frequently applied holistic EFM in the world, with *c.* 15 standard applications in South Africa (Tharme and King, 1998; King *et al.*, 2000), and single applications in Australia (Arthington and Long, 1997; Arthington and Lloyd, 1998) and Swaziland (AfriDev/Knight Piesold Joint Venture and JTK Associates, 1999). Moreover, modified forms of this bottom-up methodology, the intermediate and comprehensive determination methods, for calculation of the ecological reserve founded on legislative reforms (DWAF, 1999d,e), have been applied or are in the process of being used for collectively 33 South African rivers (DWAF, unpublished data, 2001). Within several such applications, a newly established flow stress or response (FSR) method (O'Keeffe *et al.*, 2001) uses relationships between low (and high) flows and corresponding ecological stresses to generate time series of stress indices, linked to a river's flow regime. These stress regimes allow for the examination of a range of flow scenarios, each with expression of the potential risk of change in river ecological condition.

Recently evolving from the BBM and other similar EFMs as an interactive, top-down holistic methodology comprising four modules (biophysical, social, scenario development and economic), the downstream response to imposed flow transformations (DRIFT) process (Metsi Consultants, 2000; King *et al.*, this issue) offers innovative advances in environmental flow assessment. It focuses on identification, by a multidisciplinary team, of the consequences of reducing river discharges from natural, through a series of flow bands associated with particular sets of biophysical functions, and of specific hydrological and hydraulic character, in terms of the deterioration in system condition. As the methodology is scenario-based, there is considerable scope for the comparative evaluation of the consequences of a number of recommended flow regimes. Additionally, links between social consequences for subsistence users, are evaluated alongside ecological and geomorphological ones, and economic implications in terms of mitigation and compensation, which evolved through its application in southern Africa, for the Lesotho Highlands Water Project (C. A. Brown and J. M. King, pers. comm.).

Very recently, a scenario-based combination of the BBM and DRIFT, here referred to as the adapted BBM-DRIFT, simplified to deal with developing country constraints in terms of available resources (data, time and finances) and instances where clear dependencies by rural people on riverine resources exist, has been tested in Zimbabwe (Steward, 2002).

Most applications of holistic EFMs in Australia, especially early on, have centred on the holistic approach (Arthington *et al.*, 1992; Arthington, 1998a) as well as the use of expert panel approaches (broadly discussed in Cottingham *et al.*, 2002) such as the expert panel assessment method (EPAM; Swales *et al.*, 1994; Swales and Harris, 1995) and the more developed scientific panel assessment method (SPAM; Thoms *et al.*, 1996) (Appendices I and II). Increasingly comprehensive, diverse methodologies have emerged over the past few years from this basis; notable among these is the flow restoration methodology (FLOWRESM; Arthington, 1998b; Arthington *et al.*, 2000), developed during an EFA for the Brisbane River, and aimed specifically at addressing EFRs in river systems exhibiting a long history of flow regulation and requiring restoration. Following an alternative route, the habitat analysis method and extensive basin-wide water allocation and management planning (WAMP) initiatives in Queensland, Australia (Burgess and Vanderbyl, 1996; Burgess and Thoms, 1998; Arthington, 1998a; acted as precursors to the establishment of the benchmarking methodology (Department of Natural Resources (DNR), cited in Arthington, 1998a), thus far the sole holistic EFM specifically designed to assess the risk of environmental impacts due to river regulation at a basin scale (Arthington, 1998a). The benchmarking methodology has been adopted as the standard methodology for determining environmental flow objectives (and associated performance indicators) in Queensland's water resource planning framework, applied or in use in eight local river basins (Whittington, 2000). The methodology is geared to relating information on alteration of the natural hydrological regime with ecological and geomorphological impacts, by evaluating the river condition (in terms of all major ecosystem components, e.g. riparian vegetation, fish and hydraulic habitat) of a range of sites (preferably, but not necessarily within the study river system) selected to illustrate the effects of various degrees of change in hydrological regime. A suite of core flow statistics or indicators deemed to be of ecological relevance are used to describe the features of the flow regime of the study river. Individual flow indicators are then used to develop benchmarking models, linking flow regime change with ecological responses, which are subsequently used to establish a risk assessment framework to evaluate future water resource management scenarios in terms of their potential environmental impacts.

It is noteworthy that the River Babingley (Wissey) method, developed in England (Petts, 1996; Petts *et al.*, 1999), appears to represent the only documented holistic EFM developed or applied outside the southern hemisphere countries of Australia and South Africa. Although it originated independently of other holistic EFMs, it appears to exhibit several features in common with several of them, including the holistic approach and BBM.

Arthington *et al.* (1998a) observe that bottom-up holistic EFMs are likely to continue to be applied most commonly in the near future, but suggest that ultimately, the most rigorous approach would be a combined bottom-up/top-down approach. The former process would be used to derive one or several modified flow regimes, with subsequent risk-based evaluation of the ecological consequences of each regime using a top-down procedure incorporating benchmarking. Cross-country exchange of expertise (e.g. during applications of the BBM and DRIFT) has been found to be integral in promoting the uptake and rapid development of holistic EFMs of all forms in both countries in which they predominate, as well as in developing countries such as Zimbabwe and Lesotho. A highly significant result of the analysis conducted in this paper is the strong expression of interest by at least 12 countries in Europe, Central-South America, Asia and Africa, in holistic methodologies (Appendix I).

Combined methodologies and other approaches

A fairly high number of methodologies (16.9% of the global total) representing some combination of hydrological, habitat-discharge and/or partial holistic approaches have been developed and applied across the world (Figure 2), although the figure may, in part, reflect the difficulties inherent in correctly classifying several of the methodologies documented in the literature (especially those for which information was limited or abstruse). Of these, roughly half are clearly associated with an established procedure. The methodologies range from the country-specific, combined hydraulic and biotic Basque method (Docampo and De Bikuña, 1993), through to more broadscale approaches, such as frameworks based on the habitat evaluation procedure (e.g. Duel *et al.*, 1996), and use of physical biotopes/functional habitats (Appendix I). The most commonly applied combination EFM was recorded as the managed flood release approach of Acreman *et al.* (2000) or similar approaches based on experimental flow releases, mostly applied across Subsaharan Africa, as well as in Asia and the USA.

As envisaged, the smallest proportion of the overall total number of methodologies (6.8%; Figure 2) was found for the ‘other’ category comprising alternative approaches for assessing EFRs (and professional judgement). The 13 approaches, the majority of which utilize multivariate regression analyses, were not developed primarily for EFAs and presently possess extremely limited scope in this regard. However, a few, for example, the river invertebrate prediction and classification system (RIVPACS; Wright *et al.*, 1996), have been used to recommend environmental flows (e.g. Brown *et al.*, 1991, cited in Dunbar *et al.*, 1998) and/or exhibit potential for future extension as tools at various stages of such assessments (e.g. Choy *et al.*, 2000, for invertebrates; Kennard *et al.*, 2000, for fish).

Trends in methodology types among world regions

The information presented in Appendix I for individual countries was aggregated by type and region, to identify any trends in the methodology types applied for six predefined world regions, as depicted in Figure 3. No cognisance was taken of actual numbers of applications for methodologies within each type in the calculation of proportions.

Although all regions employ hydrological methodologies, Europe (here including the Middle East) and North America were found to apply a markedly higher percentage of them than the remaining regions, at 38% and 26%, respectively (Figure 3). In contrast, very few such EFMs are in use in the Asian Pacific, outside of Australia and New Zealand.

The regionally limited scope of hydraulic rating methodologies is evidenced by the application of disproportionately more hydraulic rating methodologies in North America than in any other world region (76%), with only two other regions (Europe and Australasia) having used these EFMs to any great extent to date (Figure 3).

Again, with habitat simulation methodologies, North America is at the forefront, with more than half the established methodologies recorded in the United States. All of the remaining five regions have used such techniques, although at low levels of application in Africa and Latin America (Figure 3).

The majority of the diverse range of holistic EFMs currently available have been used within the Australasian region, at 65% of the overall total (Figure 3), though solely in Australia (the distinct differences between Australia and New Zealand in the development and application of EFMs are discussed further below). Africa was recorded as possessing the next highest representation of this methodology type, principally as a result of the range of methodologies in place in South Africa, with Europe (only the UK) being the other region to employ such an approach. The absence of any applications of such EFMs in North America is striking, and highlights the particular emphasis on habitat simulation methodologies characteristic of the region where they originated. Europe has applied the most combination EFMs and other approaches of all regions, at 39% and 57%, respectively, while these two types have had little or no exposure in South and Central America (Figure 3).

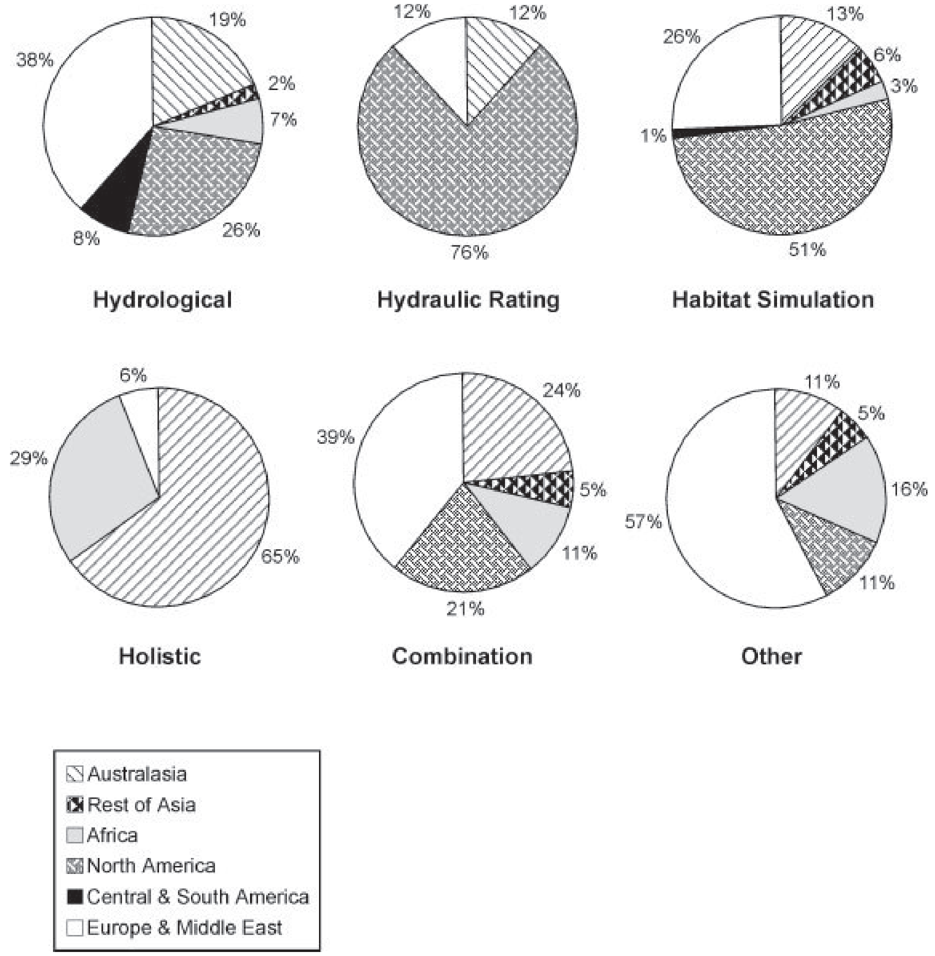

Figure 3. Relative percentage use of each of the six types of environmental flow methodologies for different world regions

The full suite of methodology types is employed only in Australasia (Australia) and Europe, while only the two types utilized by all regions (i.e. hydrological and habitat simulation methodologies) are represented in Central-South America.

Country-specific trends

The numbers of individual EFMs of different types and the proportions of the corresponding global totals, for the ten countries for which the highest total numbers of methodologies were recorded, are summarized in Table II. The proportional representation of the six methodology types for each of these same countries is illustrated in Figure 4.

Significantly, the USA has applied more than double the number of methodologies of the next ranked country, at 77 (37% of the global total), demonstrating a considerable allocation of resources to EFAs, and reflecting the comparatively long history of such assessments in this country. However, many of the methodologies applied in the earlier years of EFAs, including most of the 19 or so hydraulic rating EFMs (a considerable 83% of the world total for this EFM type), have since fallen into disuse (Appendix I). Of the ten countries examined, the USA had the highest use of individual hydrological methodologies (although regionally, Europe emerged above North America) and habitat simulation EFMs (half the global total documented).

Australia was found to rank second globally, in numbers of approaches applied (about 37), and with the UK, had tested all broad types of methodology locally. Australia and South Africa, in combination, accounted for the vast

Table II. Numbers of environmental flow methodologies (EFMs) of different types and proportions of global totals, for the ten countries for which the highest total numbers of methodologies were recorded

Country	No. EFMs (% of GT 207)	Total no. types (max 6)	No. Hydro (% of GT 61)	No. Hydraulic (% of GT 23)	No. Habitat Sim (% of GT 16)	No. Holistic (% of GT 58)	No. Combin (% of GT 14)	No. Other (% of GT 35)
USA	77 (37%)	5	20 (33%)	19 (83%)	29 (50%)	—	8 (23%)	1 (7%)
Australia	37 (18%)	6	11 (18%)	1 (4%)	6 (10%)	11 (69%)	6 (17%)	2 (14%)
UK	23 (11%)	6	10 (16%)	1 (4%)	1 (2%)	1 (6%)	3 (9%)	7 (50%)
Canada	22 (11%)	4	9 (15%)	1 (4%)	10 (17%)	—	—	2 (14%)
South Africa	20 (10%)	5	6 (10%)	—	2 (3%)	5 (31%)	4 (11%)	3 (21%)
New Zealand	20 (10%)	5	8 (13%)	2 (9%)	6 (10%)	—	3 (9%)	1 (7%)
Spain	14 (7%)	4	8 (13%)	—	4 (7%)	—	1 (3%)	1 (7%)
Italy	11 (5%)	5	4 (7%)	1 (4%)	1 (2%)	—	4 (11%)	1 (7%)
France	10 (5%)	3	3 (5%)	—	6 (10%)	—	1 (3%)	—
Portugal	10 (5%)	4	7 (11%)	1 (4%)	1 (2%)	—	1 (3%)	—

Abbreviations: GT, global total; Hydro, hydrological; Hydraulic, hydraulic rating; Habitat Sim, habitat simulation; Combin, combination. A dash indicates no recorded application of the specific methodology type.

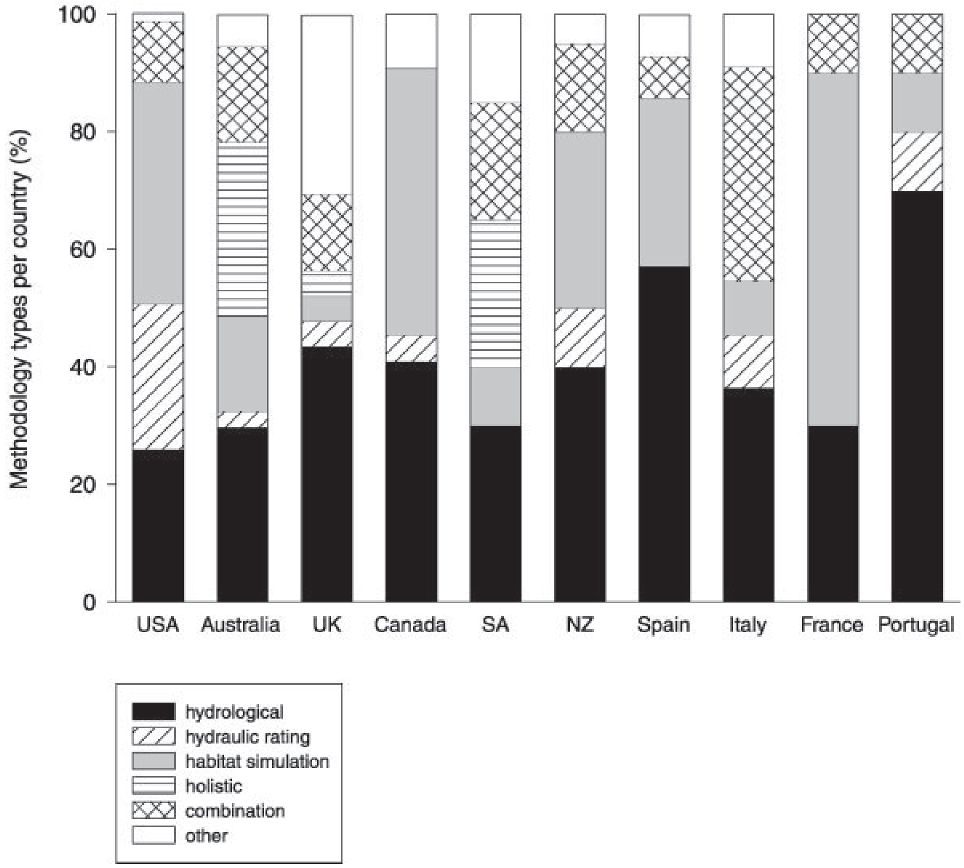

Figure 4. Relative percentage use of different types of environmental flow methodologies for the ten countries for which the highest total numbers of methodologies were recorded (ranked from highest to lowest total number)

majority of applications of holistic EFMs globally, as well as of combination and alternative approaches. Interestingly, Figure 4 highlights the fact that New Zealand has followed a vastly different trajectory of development and application of methodologies from that of Australia, with considerable investment in hydrological and habitat simulation EFMs, but negligible attention directed at holistic approaches. As indicated in the regional analysis, the USA and Canada also have not invested much, if any, effort in exploring holistic methodologies *per se*, although they are undertaking focused research on the ecological relevance of various elements of the flow regime (e.g. B. D. Richter, pers. comm.).

The UK, Canada, South Africa (most active in Africa) and New Zealand were identified as engaged at similar levels in environmental flow research (20–23 EFMs applied, Table II). The presence of the USA, Australia and Canada in the five most active countries, may in part reflect the variety of approaches adopted at state level, in contrast with possibly more unified national-level initiatives elsewhere.

The remaining group of countries, for which a fairly high number of different methodologies have been documented (*c.* 10–14), are located within southwest Europe. Of these, Portugal and Spain have invested considerable effort in hydrological methodologies, France in habitat simulation EFMs, and Italy in hydrological and combined approaches (Figure 4). For South-Central America and Asia (not represented in Table II), Brazil and Japan are at the forefront of regional developments in environmental flow assessment (Appendix I).

Developed versus developing countries

Just over half (52%) of the countries representing the developed world were shown to be routinely involved in environmental flow initiatives, at various levels of advancement (Tables II). In stark contrast, in developing countries (WRI, 2002), the field of EFAs is nascent or only very locally active, with merely 11% of such countries recorded as applying EFMs.

Presently, 49 countries are formally designated ‘Least Developed Countries’ (LDCs) by the Economic and Social Council of the United Nations, on the basis of the criteria: low income, human resource weakness and economic vulnerability (United Nations Conference on Trade and Development website, 2002). Of these, five African countries (or 10%) have implemented some kind of EFA. In all cases but one, a managed flood release approach was adopted, focused on river floodplain restoration for fisheries production and the sustainment of dependent livelihoods (Acreman *et al.*, 2000). Notably, the holistic DRIFT process was used in the fifth case, for Lesotho, also with cognisance of direct social and economic implications for the population at risk (King *et al.*, this issue).

CONCLUSIONS

Examination of the emerging trends in evidence from this survey of the methodologies of various types developed and applied globally, indicates several paths of progress in environmental flow assessment. As identified in King *et al.* (1999), and confirmed in this review, there is a widespread move towards hierarchical application of environmental flow methodologies in many countries, with at least two stages to the framework: (1) reconnaissance-level assessment, primarily using hydrological methodologies; (2) comprehensive assessment, using either habitat simulation or holistic methodologies. For example, two-tier application of methodologies occurs at a state-wide level in Alaska (Estes, 1996), and at a national scale in the Czech Republic (Bernadová, 1998). Several countries, including South Africa (Tharme, 1997; DWAF, 1999d), the UK (Petts *et al.*, 1996, cited in Dunbar *et al.*, 1998), and Australia (Arthington *et al.*, 1998a), advocate the use of flexible, multiple-level hierarchies over a range of spatial scales, driven by the availability or access to resources, including time, data, finances, and technical capacity. The South African hierarchy of methodologies provides a recent example, from rapid, simple desktop estimate to comprehensive determination, for allocating the reserve for basic human needs and ecosystem protection (including the ecological reserve, the EFR; DWAF, 1999d), the only two water rights by law. The process by which the reserve framework became established (Palmer, 1999) highlights the instrumental role of revised freshwater policy and legislation, in addition to the existence of suitable types of environmental flow methodologies and demonstrable capability in the execution of EFAs, in revolutionizing the arena of EFAs on a national scale. Similar initiatives are underway elsewhere at national and broader scales, for example in Australia, in relation to the national water reform process and policy guidelines for the allocation of water for ecosystems (Agriculture and

Resource Management Council of Australia and New Zealand (ARMCANZ) and Australian and New Zealand Environment and Conservation Council (ANZECC), 1996), as well as for the European Union, in line with the Water Framework Directive (Lanz and Scheuer, 2001).

The first stage of an EFA is typically aimed at a national or basin-wide planning or reconnaissance level, and characteristically invokes the use of hydrological EFMs. Such methodologies, currently numbering above 60, a significant 30% of the remarkably high (207) number of methodologies worldwide, and in use in all world regions examined, are particularly well suited for adoption at this level of assessment. This is primarily due to their rapid, low-resource intensity application at a desktop level, providing routine, simple yet low resolution estimates, of quantities of water to be set aside for environmental purposes.

In recent years, more sophisticated hydrology-based methodologies, most notably RVA (Richter *et al*., 1996, 1997), have drawn interest outside of the countries in which they were developed, through their increased emphasis on flow variability and/or utilization of ecologically relevant, multiple hydrological indices in the determination of environmental flows. Such advances represent a means of redressing the common tendency, still observed in many countries, of applying hydrological indices and methods such as the Tennant method (Tennant, 1976) arbitrarily and indiscriminantly across different countries, geographic regions and river types, without sufficient understanding of the system-specific ecological implications of the minimum flows they represent, or of the bounds of transferability.

Beyond this first level of environmental flow assessment, two main avenues of development of methodologies are in evidence at present. In developed countries of the northern hemisphere particularly, as well as in developing countries that receive technical support for EFAs from the USA or Europe, there is ongoing application of habitat simulation methodologies, which have evolved rapidly from now largely obsolete hydraulic rating techniques, to become the second most commonly applied group. Although some 58 individual approaches have been reported in different countries across the world, IFIM (Stalnaker *et al*., 1994; Milhous, 1998a) far exceeds all established hydraulic-habitat modelling approaches of similar type, with applications in at least 20 countries. In most instances, such methodologies remain biased towards the assessment of the flow requirements of target fish species, with recent efforts concentrated on major advances in multidimensional habitat modelling and the inclusion of complex, spatially explicit habitat metrics. This is despite the still largely unexplored potential some of these methodologies possess for addressing flows for other biota or ecosystem components.

The second branch of development, that of holistic methodologies aimed at assessing the EFRs of the entire riverine ecosystem, and with explicit links to all aspects of the hydrological regime, is historically less well entrenched in the field of environmental flow assessment, originating in the early 1990s (Tharme, 1996). However, prolific development and application of some 16 methodologies of this type (already 7.7% of the global total) within a decade, have provided the impetus for significant, new directions in EFAs, accentuating the shift from a single-species to a biodiverse, whole-ecosystem focus. Although the use of such methodologies presently remains strongly based in Australia and South Africa, with marked bilateral collaboration in research and applications, holistic EFMs have attracted growing international interest, particularly in the Southern African Development Community (SADC), as well as southwestern Europe, southeast Asia and Latin America.

Interestingly, South Africa has concentrated its efforts thus far on rigorous, routine application of this methodology type, using the BBM (King and Louw, 1998; King *et al.*, 2000) and related approaches for standard reserve determinations, with the BBM the most frequently applied holistic methodology globally. In contrast, Australia has invested resources in developing and applying a particularly high diversity of holistic methodologies.

Although the emphasis thus far has been on prescriptive, bottom-up methodologies for construction of a recommended environmental flow regime, there have been significant advances recently in interactive, top-down processes; Arthington *et al*. (1998a) provide a convincing argument for combining the two kinds of approach in future. Notably, of the top-down approaches, the South African DRIFT process (King *et al*., this issue) has emerged from the foundations of the BBM, as a frontrunner of scenario-based methodologies, with explicit consideration of social consequences for subsistence users, linked to the biophysical consequences of flow regulation, and the associated economic implications. Another singularly important advance has been the establishment, in Queensland, Australia, of the benchmarking methodology, demonstrated to be particularly suitable for the generation of risk assessment frameworks for basin-scale evaluation of the potential environmental impacts of future scenarios of water resource management, especially for relatively poorly studied systems (Arthington, 1998a; Bunn, 1998).

Significantly, holistic methodologies have yet to be explored in depth in the northern hemisphere, possibly in large part due to the long-standing reliance on and research investment in habitat simulation EFMs to generate environmental flow recommendations for economically important fish species. This author and others (King *et al.*, 1999) contend, however, that holistic methodologies are typically more appropriate than habitat simulation methodologies *per se*, particularly from the perspective of developing countries. This is due to the absolute need of such countries to focus on protection of the resource at an ecosystem scale, as well as the strong livelihood dependencies on the goods and services provided by aquatic ecosystems. Furthermore, the inherent capacity of holistic methodologies to further incorporate advanced single-issue techniques, such as hydraulic and habitat modelling tools, and other types of predictive models, as these become available, as well as their consideration of multiple ecosystem components, is liable to render them increasingly suitable in this regard. Several of the more advanced holistic, as well as combination approaches (16.9% of the world total), recorded in use underscore the potential for future coupling of tools or cross-pollination among different methodology types, perhaps generating a new multi-scale typology of highly adaptable techniques (the 'tool-kit' referred to below).

This overview of global trends has clearly shown that the greatest activity in environmental flow work resides in developed countries, in North America (with the United States having applied a disproportionately high number of methodologies, at 37% of the global total), Australasia (with Australia ranked second worldwide), Europe, and South Africa. Furthermore, it has exposed marked gaps in terms of environmental flow initiatives for entire world regions and individual countries, especially those accorded developing or least developed status, where awareness of and access to the vast amount of global expertise is limited. The lack of endeavour in many such countries is apparent even in water-scarce parts of the world, where the availability, quality and sustainability of freshwater resources play a crucial role in socio-economic upliftment. Moreover, it is despite existing and proposed intensive water-resource development, particularly in the form of river regulation by large dams, with an estimated average of 160–320 new large dams being constructed annually worldwide (WCD, 2000). This is particularly true for China and India, with both countries featuring in the top five countries worldwide in terms of both numbers of existing (Table I) and proposed large dams, yet without substantial evidence of investment in environmental flow assessment. Also, in South-Central America at present, only two types of methodologies are used, with the lowest recorded incidence of EFAs worldwide. This is regardless, for instance, of current plans for over 70 dams for the Amazonian region of Brazil alone (Pringle *et al.*, 2000), as well as the massive, transboundary 20-year Hidrovia project, for which the first stages are under construction, affecting Brazil, Argentina, Uruguay, Paraguay and Bolivia (Abramovitz, 1995).

These trends suggest that many countries have not yet recognized and embedded in water resources policy and management the critical importance of the hydrological regime as the primary driver of ecological processes in river–floodplain systems (Junk *et al.*, 1989; Poff *et al.*, 1997; Richter *et al.*, 1997) and the role of environmental flows in the long-term maintenance and sustainability of such systems, or have not yet made such assessments a priority (Tharme, 1996). However, the analysis of global trends also yielded encouraging signs of the initiation of environmental flow work in several countries, among others the lower basin countries of the Mekong River (the third largest river in Asia by drainage basin size, and scheduled for intensive water resource development; Dudgeon, 2000), Indonesia, Mozambique, Brazil and Zimbabwe. Such initiatives are often, at least in part, a result of the sourcing of expertise from neighbouring countries where the science is already well established or of international collaborative research projects.

Large, often transboundary river basins, several with complex, interrelated multiple-component aquatic ecosystems, present a special challenge still to be met in environmental flow assessment, at both statewide and country scales. There are an estimated 261 to 280 such basins traversing the political boundaries of two or more countries, accounting for some 80% of river flow and affecting roughly 40% of the world population (Wolf *et al.*, 1999, cited in WCD, 2000; GCI, 2000). Cross-border collaboration would seem essential in such situations. However, to date, with the majority of EFAs for transboundary systems, neighbouring countries have most often been excluded from the assessments. There is also likely to be a need for increased expenditure of effort in addressing environmental flow issues for river restoration and dam decommissioning projects, both of which are on the upsurge (WCD, 2000). Furthermore, the vast majority of methodologies available globally have focused exclusively on river systems, with the scope for adaptation and extension of such approaches to other aquatic ecosystems (e.g. groundwater-dependent wetlands and estuaries) being, for the most part, weakly explored.

Realistically, the selection of an appropriate environmental flow methodology for application in any country is likely to be context-specific and primarily constrained by the availability of appropriate data on the river system of concern, as well as local limitations in terms of time, finances, expertise and logistical support (King *et al.*, 1999). However, the still observed, rather arbitrary or *ad hoc* application of certain EFMs in numerous countries should be replaced by the use of a comprehensive hierarchically arranged suite of methodologies, if appropriate scientifically (and legally) defensible results are to be achieved. An internationally collaborative research effort might facilitate the establishment of such a framework-based tool-kit, founded on best practice and sufficiently flexible to meet the needs of each situation and country. Additionally, it is imperative that more concerted efforts are made to implement, in their entirety, the environmental flow regimes recommended for rivers, to ascertain their relative success through post-implementation monitoring and appropriate evaluation techniques, and subsequently, to refine the flow recommendations. As Arthington *et al.* (1998a), King *et al.* (1999) and Gippel (2001) point out, these crucial areas of environmental flow assessment have received negligible attention worldwide.

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Appendix I. Environmental flow methodologies currently in use, historically used but probably superseded by more recent approaches,# or recommended for potential future application,* for rivers in various countries worldwide. Countries are listed in alphabetical order, with regional affinities designated as follows: [a]Australasia (Australia and New Zealand); [b]rest of Asia; [c]Africa; [d]North America; [e]Central and South America (including Mexico and the Caribbean); [f]Europe and the Middle East. Methodologies are listed according to type, namely: 1) hydrological; 2) hydraulic rating; 3) habitat simulation; 4) holistic; 5) combination; 6) other. Where reported, the most widely used or preferred methodologies are highlighted in bold. ? = unconfirmed. Abbreviations are listed in the footnote. Major sources of information used include: Stalnaker and Arnette (1976); Reiser *et al.* (1989a); Tharme (1996, 1997, unpublished report); Dunbar *et al.* (1998); Arthington (1998a); Arthington and Zalucki (1998a); and King *et al.* (1999), as well as personal communications with at least 60 country experts (see below and Acknowledgements). Selected references for methodology development and case studies of application in individual countries are provided, where numbered superscripts 1-225 are used to distinguish the various methodologies tabulated

Country	Environmental flow methodologies	References for case studies
[a]Australia	**1)** [1]Tennant Method; [29]Q_{95} (or a multiple thereof); [33]FDC analysis & various percentiles (incl. ecological & geomorphological data); [14]Various percentages of pre-regulation MAR (e.g. 22%, 10%); [50]Texas Method; [61]Orth & Leonard Regionalization Method; [60]R_Q Index of Disturbance; [23]Q_{80} (of unregulated mean daily flow regime); [58]Flow Translucency Approach; [53]Modified Hoppe & Finnell Method (coupled with FDC analysis); [45]VHI; *[44]RVA **2)** [65]Wetted Perimeter Method **3)** [89]**IFIM**; [95]RHYHABSIM; [118]**MTA**; [143]Physical Habitat Analysis; [143]Fish Habitat Analysis; [144]Habitat Duration Analysis (median or other percentile of habitat condition) **4)** [147]**Holistic Approach** (incl. use of ADVICE Hydrological Program, RHYHABSIM, *multivariate index of environmental effectiveness; *IFIM-based analyses); [148]BBM; [153]**EPAM**; [154]SPAM (incl. use of IQQM); [163]Snowy Inquiry Methodology; [156]**Habitat** Analysis Method (incl. TAP & IQQM); [157]**WAMP Expert Panel Method** (incl. IQQM); [158]**Benchmarking Methodology** (incl. IQQM, typically in association with Queensland WAMP, for water Resource Plans); [159]**FLOWRESM** (incl. IQQM); [161]Flow Events Method; [160]Local FLOWRESM-type approaches for river restoration; *DRIFT (specialist development and input overseas, but not applied locally) **5)** [168]Studies of threshold components of flow regime; [186]DWR case-specific holistic-based approaches (minimising deviation of flow regime from natural); [187]Thomson River Fish Habitat-Flow Approach; [169]Wimmera River Habitat-based Approach (primarily fish habitat, incl. water quality & experimental flow release); #[188]Hall Fish Habitat Approach; [189]Physical Biotopes approaches **6)** PJ; [213]Means of recommended Qs derived from multiple methodologies	[89]Koehn, 1986; [1,29,33,53,89,118]Richardson, 1986; Campbell, 1986; [89]Kinhill Engineers, 1988; [89,143,188]Hall, 1989; Pigram & Hooper, 1992; [147]Arthington *et al.*, 1992; [1,33,89,118,147,153,169]Arthington & Pusey, 1993 (& refs. cited: [169]Anderson & Morison, 1988a, b; [65,143]Tunbridge & Glenane, 1988; [89,95]Gan & McMahon, 1990; [33,143,188]Hall, 1991; [95,147]Arthington *et al.*, 1992, a, b); [33,45,147,153]Cross *et al.*, 1994 (& refs. cited: [1,33,50,61,213]Green, 1993; [168]Cooney, 1994b; [168]Ardill & Cross, 1994); [1,14,33,89,147,153,186]Growns & Kotlash, 1994; [53,118,143,153]Swales *et al.*, 1994; [153,156]Walter *et al.*, 1994; [14,187]Gippel *et al.*, 1994; [89,144]Gippel & Stewardson, 1995, [65]1998; [153]Swales & Harris, 1995; [1,147]Karim *et al.*, 1995; [65, 89]Davies & Humphries, 1995; SGCMC, 1996, cited in Stewardson, 2001; [154]Thoms *et al.*, 1996; [156]Burgess & Vanderbyl, 1996; [189]Stewardson & Gippel, 1997 (& refs. cited: [23]Knights & Fitzgerald, 1994; [60]Gehrke *et al.*, 1995); [44,95,147,153,154,156,160]Arthington 1998a (& refs. cited: [89]Pusey & Arthington, 1991; Arthington *et al.*, 1992b; Arthington, 1994; Blühdorn & Arthington, 1995; Young *et al.*, 1995; [153]SREP, 1996; [153,163]Bishop, 1996; [153]Cooksey, 1996; [153]CWPR, 1996; [147]Davies *et al.*, 1996; [156,157,158]Burgess & Thoms, 1997; [147]Growns & Growns, 1997; [147]Scott *et al.*, 1998; McCosker 1998a, b; [157,158]Vanderbyl, 1998; DNR 1998a, b); [159]Arthington, 1998b; [156,157,158,159]Arthington & Zalucki, 1998a, b; [148]Arthington & Lloyd, 1998; Arthington *et al.*, 1998a, b, [159]2000; [1,61,153,154]Pusey, 1998; Brizga, 1998; [157,158]Bunn, 1998; [157,158]Burgess & Thoms, 1998; [157,158]Thoms & Swirepik, 1998, cited in Bragg *et al.*, 1999; [157,158]Whittington, 2000; [161]Stewardson, 2001; [161]Cottingham *et al.*, 2001; [58]Gippel, 2001 (& refs. cited: [163]SWI, 1998; [163]Gippel *et al.*, 1999); [158]DNR, 1998, 2000; [158]Brizga, 2000; [158]Brizga *et al.*, 2000a, b; [158]Brizga *et al.*, 2001a, b, c, d); pers. comm: [44]T. Ladson; [158]A. Arthington; M. Stewardson; C. Gippel; M. Kennard; I. Campbell
[f]Austria	**1)** VHI? **3)** [115]Quantitative fish habitat modelling (unspecified); IFIM? **5)** [166]Holistic framework combining expert opinion, various criteria (unspecified), a 7-point naturalness scale & elements of IFIM/PHABSIM	[115,166]Dunbar *et al.*, 1998

[f]**Belgium**	**1)** VHI? **5)** [190]Hydrograph Reconstruction Approach (Meuse River, shared with Netherlands & France)	[190]Salverda *et al.*, 1996
[e]**Brazil**	**1)** [38]**50% or** [39]**70% of 7Q10 (reference flow)**; [26]**10% of Q_{90}** (regulated flow); [24,25]**5–20% of Q_{90} (reference flow)** **3)** [89]IFIM **5)** *Ecohydrological modelling	[24,25,26,38,39,89]A.D. Benetti *et al.*, unpubl. paper 2002; pers. comm: [24,25,26,38,39,89]A. Benetti; [89]R. Sarmento
[f]**Bulgaria**	**1)** [29]Q_{95} (based on Mean Monthly Q) **5)** [185]Correlations between Q_{95}, four groups of physico-chemical & one group of biotic indices	[29,185]Dacova *et al.*, 2000
[b]**Cambodia**	**4)** *Holistic methodologies **5)** *Habitat-based hydrological modelling linked to fish populations (incl. SLURP Model, satellite remote sensing, for lower Mekong Basin countries)	pers. comm: IWMI; I. Campbell
[c]**Cameroon**	**5)** [164]Managed Flood Releases Approach (incl. socio-economic links)	[164]Acreman *et al.*, 2000
[d]**Canada**	**1)** [1]**Tennant Method**; [2]**Tessman Modification of Tennant Method**; [6]Two-level Seasonal Modified Tennant Method (with PJ); [11]**25% MAF**; [37]7Q10; [19]Median Monthly Flow; [47]**(New England) ABF Method**; [24]Q_{90}; RVA **2)** [65]**Wetted Perimeter Method** **3)** [89]**IFIM** (primarily PHABSIM); [93]Fish Rule Curve Method (incl. PHABSIM/habitat time series, BSPs, HDCs); [109]**River2D Model** (incl. sediment transport module); [111]2D/3D hydrodynamic modelling; [98]EVHA; [96]RHABSIM; [99]RSS (HABITAT Model); [102]HABIOSIM; [119]Newcombe's Methodology; [140]WSP Hydraulic Model (with PJ) **6)** PJ; [203]Correlations of fish year class to spawning flow	[119]Newcombe, 1981; [89]Bietz & Kiell, 1982; [89]Shirvell, 1986; [1,11,65,89,140]Reiser *et al.*, 1989a; Thompson, 1992; [1,11,19,24,37,47]Caissie & El-Jabi, 1994; [11,24]Caissie, 1995, cited in Dunbar *et al.*, 1998; [89,111]Leclerc *et al.*, 1995; [6,89]Scruton & LeDrew, 1996; [89,96,98,99,111]Scruton *et al.*, 1996; [89,93]Locke, 1996 (& refs. cited: [1]Longmore & Stenton, 1981); [89]Tharme, 1996, [109]in prep.; [2,89,102,203]Dunbar *et al.*, 1998; [109]University of Alberta web site, 2001; pers. comm.: C. Estes; C. Katopodis; R. Milhous; B. Richter
[e]**Chile**	**1)** [10]**10% MAF** or [16]**Mean Monthly Flow** **3)** [89]PHABSIM component of IFIM **4)** *[148]BBM	[10,89]H. D. Davis & M. F. Riestra, unpubl. abs. 2002; [10,16,148]M. Davis, pers. comm.
[f]**Czech Republic**	**1)** [Bern35]**Q_{355} or** [36]**Q_{364}** (where $Q_{355} = 0$, present-day hydrology); [45]VHI **3)** [89]**IFIM** (incl. 2-D/3-D hydrodynamic modelling); [112]hydraulic habitat modelling	[35,36,112]Bernadová, 1998 (& refs. cited: Bernadová & Mrázek 1995, 1996); [89]Blažková *et al.*, 1998; [89,112]Blažková, 1998; [89]Jiřinec & Mattas, 1998; [45]D. Mattas, pers. comm.
[f]**Denmark**	**1)** [20]**Median of Annual Minima** (Median Q_{min}; or a proportion thereof, depending on river value); [33]Low flow indices from FDC analysis (unspecified); [40]Flow indices from frequency analyses (unspecified)	[20]Miljoestyrelsen, 1979, cited in Jowett, 1997; [20]Clausen & Rasmussen, 1988, cited in Dunbar *et al.*, 1998; [33,40]Dunbar *et al.*, 1998
[f]**Finland**	**3)** [98]EVHA; [90]PHABSIM (incl. HSI curves, primarily for fish habitat restoration) **6)** PJ; [208]Direct use of GIS-based studies of physical habitat for fish/invertebrate species	Sinisalmi 1997; [98]Riihimäki *et al.*, 1996, cited in Dunbar *et al.*, 1998; [208]Muotka *et al.*, 1996; [90]Huusko & Yrjänä, 1996

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Appendix I. *Continued*

Country	Environmental flow methodologies	References for case studies
[f]**France**	**1)** [8]**1/40th of annual mean flow** (i.e. 2.5% MAF, existing WRDs); [10]**1/10th of annual mean flow** (i.e. 10% MAF, over minimum 5-year period, new/renewed WRDs); [13]20% MAF (for MAF $> 80\,\mathrm{m^3\,s^{-1}}$) **3)** [98]**EVHA**; [89]IFIM (or 'microhabitat' methodology); [106]Linked statistical hydraulic & multivariate habitat use models; [103]ENSA Toulouse Method; [113]Fish population modelling within an IFIM-type framework; [145]Continuous Over (Under) Threshold Procedure (incl. habitat duration & spell analyses); [97]CASIMIR **5)** [172]GIS-based AGIRE (multipurpose, incl. habitat simulation)	Belaud *et al.*, 1989, [89]Souchon & Valentin, 1991, cited in Stewardson & Gippel, 1997; [10,13]Docampo & De Bikuña, 1993; [98]Ginot 1995, cited in Dunbar *et al.*, 1998; [98]Pouilly *et al.*, 1995, cited in Lamoroux *et al.*, 1999; [145]Capra *et al.*, 1995; [145]Breil & Capra, 1996 (& refs. cited: [89]Valentin *et al.*, 1994); [8,10,89]Merle & Eon, 1996; [103,113,172]Dunbar *et al.*, 1998; [106]Lamoroux *et al.*, 1998, 1999; [97]K. Jorde, pers. comm.
[f]**Germany**	**1)** [17]**Mean Q_{min} or a** [18]**fraction thereof** (with case-specific PJ); [16]MQ; [19]MNQ; [34]Q_{347} **3)** [97]**CASIMIR** (benthic shear stress, fish habitat & riparian zone models); [114]FST-hemisphere-Benthos hydraulic modelling; IFIM? **6)** PJ	[16,19,34,114]Statzner *et al.*, 1990; [97]Jorde, 1996; [97]Jorde, 1997; [97]Jorde & Bratrich, 1998; [17,18]Dunbar *et al.*, 1998; [97]Schneider, 2001; [97]K. Jorde, pers. comm.
[f]**Hungary**	**3)** [112]Hydraulic habitat simulation modelling (EFMs from Netherlands)	[112]Dunbar *et al.*, 1998
[b]**India**	**4)** *Holistic approaches	C. Trisal, pers. comm.
[b]**Indonesia**	**3)** [89]IFIM (primarily PHABSIM)	[89]S. Nakamura, pers. comm.
[f]**Italy**	**1)** [43]Regression-based regionalization of 7Q10 (based on basin area & BFI); [37]7Q10 (or $Q_{7,10}$); [34]Q_{347}; [7]Regionalization of %AAFs from Tennant Method; *[42]Regionalization of Q_{95} values, based on geology & catchment area; *[61]Orth & Leonard Regionalization Method **2)** [88]Hydraulic-based methodologies (unspecified); *[65]Wetted Perimeter Method **3)** [89]**IFIM** (primarily PHABSIM, incl. locally developed HSI curves) **4)** *Holistic methodologies (e.g. BBM/DRIFT or similar) **5)** [175]BENHFOR Procedure; [174]Po River Basin Method (links between VHI, catchment variables & water quality); [179]Modified HQI Method; [195]MORIMOR-HAFIMO Integrated Model; *[184]Singh Regionalization Method **6)** Direct use of hydrology, water quality data & various biotic indices; *Studies relating fisheries data to environmental variables	[179]Annoni *et al.*, 1996; [195]Peviani *et al.*, 1996; [34,37,43,89]Ubertini *et al.* 1996 (& refs. cited: Crosa *et al.*, 1988; [7]Casadei, 1990; Martini *et al.*, 1993/4; Santoro, 1994); [89,174]L. Viganò *et al.*, unpubl. paper 1997 (& refs. cited: Binns 1982; Marchetti *et al.*, 1991; Manciola *et al.*, 1994; Saccardo *et al.*, 1994; Cotta Ramusino *et al.*, 1994; [179]Saccardo, 1997; Benedini, 1997; Rambaldi *et al.*, 1997; [179]Gentili *et al.*, 1997); Dunbar *et al.* 1998 (& refs. cited: Saccardo *et al.* 1994; Bagnati *et al.* 1994); [175]Buffagni, 2001; [88,89,184]Vismara *et al.*, 2001; A. Buffagni, pers. comm.
[b]**Japan**	**1)** [15]OCFR (0.1–0.3 cm per 100 km^2); [15]NPF (approx. 10 × OCFR value per 100 km^2) **3)** [89]**IFIM** (primarily PHABSIM, incl. 1-D/2-D/3-D hydraulic modelling, use of multivariate HSI criteria, habitat time series & duration analyses); [113]PHABSIM-based local physical habitat simulation tools; [96]RHABSIM **4)** *Holistic methodologies (e.g. BBM)	[89,96]Tamai *et al.*, 1996; [15,89]Nakamura, 1999 (& refs. cited: Nakamura *et al.*, 1994, [113]1995; [113]Kim *et al.*, 1996; [113]Kim, 1997; [89]Tamai, 1998; [113]Nagarei, 1998; [89]Nakamura *et al.*, 1999); [89,113]S. Nakamura, pers. comm.

	5) NPFs calculated using various approaches (unspecified)	
[c]Kenya	**5)** *[164]Managed Flood Releases Approach (incl. socio-economic links, hydrological modelling)	[164]Acreman *et al.*, 2000
[b]Korea	**3)** [89]IFIM	[89]S. Nakamura, pers. comm.
[c]Lesotho	**4)** [150]DRIFT (incl. socio-economic links)	[150]Brown & King, unpubl. report, 2000; [150]Metsi Consultants, 2000; King *et al.*, this issue
[c]Mali	**5)** [164]Managed Flood Releases Approach (incl. socio-economic links)	[164]Acreman *et al.*, 2000
[c]Mauritania	**5)** [164]Managed Flood Releases Approach (incl. socio-economic links)	[164]Acreman *et al.*, 2000
[e]Mexico	**3)** *[89]IFIM	[89]R. Milhous, pers. comm.
[f]Moldavia	**3)** [112]Hydraulic habitat simulation modelling (EFMs from Netherlands)	[112]Dunbar *et al.*, 1998
[c]Mozambique	**4)** *Holistic approaches (e.g. DRIFT/BBM or similar) **5)** *[164]Managed Flood Releases Approach (inc. RVA analysis, multiple-scale ecological analyses, socio-economic links)	[164]Beilfuss & Davies, 1999; Brown & King, unpubl. report, 1999; pers. comm: B. Davies; J. King
[c]Namibia	**4)** *Holistic methodologies **5)** [164]Managed releases approach (unspecified) **6)** [202]PJ	[202]IRN, 1997; [164]Heyns *et al.*, 1998; Bethune *et al.*, 2002; S. Bethune, pers. comm.
[f](The) Netherlands	**1)** [45]VHI (use of PAWN Hydrological Model/other methods) **3)** [110]Integrated GIS-based habitat simulation model (incl. species HSI models, hydraulic & geomorphological simulation, & water quality-Q elements); [97]CASIMIR (river floodplain restoration, incl. Delft3D 2-D hydro- & morphodynamic modelling); Microhabitat simulation models for large rivers (unspecified); IFIM? **5)** [177]HEP-based framework (ecotope classification of aquatic systems, ECLAS; species potential carrying capacity model, MORRES; species HSI models; policy & alternatives analysis model, AMOEBA)	USFWS, 1980, cited in Duel *et al.*, 1996; [110]Semmekrot *et al.*, 1996; [177]Duel *et al.*, 1996; [45]Dunbar *et al.*, 1998; [97] Duel *et al.*, 2001; [97]M. J. Baptist *et al.*, unpubl. abs., 2002; [97]K. Jorde, pers. comm.
[a]New Zealand	**1)** [4]Modified Tennant Method; [10]10% AAF; [12]30% AAF; [16]30% Mean Monthly Flow; [61]Orth & Leonard Regionalization Method; [22]30–75% of 1 in 5 year low flow; [31]Q_{96}; VHI (using historic, natural flows) **2)** [68]Empirical Discharge-Water Surface Area (as habitat) Approach; [69]Hydraulic Geometry-Discharge Relationships; Wetted Perimeter Method? **3)** [95]**RHYHABSIM** (recent features addressed incl. sediment flushing, temperature, flow variability); [89]IFIM (incl. local development of HSI curves); [108]IFIM-type habitat simulation using MWD RIVERS Program; [146]Habitat methods (unspecified); [116]Food-producing Habitat Retention Approach; [92]20% Food-producing WUA Approach **5)** [194]Holistic-type approach; [198]Fish Habitat-based Regionalization Models; [193]Various (river-specific) flow event-based approaches **6)** PJ	[4]Fraser, 1978, cited in Tierney, 1986; [95]Jowett, 1982, cited in Arthington & Pusey, 1993; [89,108,193]Mosley, 1983 (& refs. cited: [193]Jowett, 1980, [89]1983; [89]Glova, 1982; Mosley, [193]1982b, c, 1983a, [68]b; O'Donnell & Moore, 1983; [16]Scarf, 1983; Robertson *et al.*, 1983; [89]Glova & Duncan, 1983); [89]Shirvell & Dungey, 1983; [108]Mosley & Jowett, 1985; [4]Tierney, 1986; [194]Hughey, 1986, cited in Karim *et al.*, 1995; [89]Scott & Shirvell, 1987; [95]Jowett, 1989, [10,12,22,31,89,92,116]1997 (& refs. cited: [146]Jowett & Wing, 1980; [69]Mosley, 1992; [22,31]Forlong, 1994; [146]Jowett *et al.*, 1995); [95]Jowett & Richardson, 1995; [61]Dunbar *et al.*, 1998 (& refs. cited: [198]Jowett, 1993a, b); [22,31]Snelder *et al.*, 1998, cited in Bragg *et al.*, 1999; I. Jowett, pers. comm.

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Appendix I. *Continued*

Country	Environmental flow methodologies	References for case studies
[c]**Nigeria**	**5)** [164]Managed Flood Releases Approach (incl. hydrological modelling, socio-economic links)	[164]Acreman *et al.*, 2000
[f]**Norway**	**1)** [46]Simple hydrological formulae (unspecified, desktop) **3)** [99]**RSS** (a habitat modelling framework, incl. BioRiv I & II macrohabitat & temperature models, HABITAT Model & Bioenergetic Model with links to 1-D/2-D/3-D hydraulic models, incl. HEC-2, ENMAG Reservoir Operation & Hydropower Production Model, HBV Rainfall-runoff Model & Param Time Series Analysis Model); #[100]RIMOS (RSS precursor); [89]IFIM (WUA); [97]CASIMIR **6)** [225]Expert method for minimum flows; [202]PJ	[100]Vaskinn, 1985, cited in Kinhill Engineers, 1988; [89]Saltveit & Heggenes, 1991, cited in Stewardson & Gippel, 1997; [99]Heggenes *et al.*, 1996; [99]Alfredsen & Killingtviet, 1996; [46,202]Dunbar *et al.*, 1998 (& refs. cited: [99]Killingtviet & Fossdal, 1992, 1994; [99]Killingtviet & Harby 1994a, b); [99,100]Alfredsen, 1998 (& refs. cited: [99]Killingtviet *et al.*, 1992; [99]Arnekleiv & Harby, 1994; [99]Harby *et al.*, 1994); [46,99]J. E. Brittain & J. Henning L'Abée-Lund, unpubl. paper 2001 (& refs. cited: [46]Ziegler, 1986; [225]Faugli, 1997); [97]Ott, 2001
[b]**Pakistan**	**5)** *[164]Managed Flood Releases Approach (incl. sediment flushing & socio-economic links)	[164]Acreman *et al.*, 2000
[f]**Portugal**	**1)** [8]**2.5% to** [9]**5% MAF** (i.e. 'Portuguese criterion', based preferentially on natural flow regime); [1]Tennant Method; [5]Ecotype-based Modified Tennant Method; [50]Texas Method; [47]New England ABF Method; [49]Basic Flow Method **2)** [65]Wetted Perimeter Method **3)** [89]**IFIM** **4)** *DRIFT/BBM or similar **5)** [196]River Enxoé Approach (temporary rivers); *Physical Biotopes/Flow Types approach	[1,8,9,65,89]Alves & Henriques, 1994; [49]Palau & Alcazar, 1996; [196]Bernardo & Alves, 1999; [196]L. Ribeiro *et al.*, unpubl. abs., 2000; pers. comm: H. Alves; J. King
[e]**Puerto Rico**	**3)** [89]IFIM	[89]Sutton *et al.*, 1997
[f]**Russian Federation**	**5)** [177]Delft Hydraulics Framework Analysis (incl. use of HEP, HSI & water quality data in scenario-based habitat modelling)	[177]De Vries, 1996
[c]**Senegal**	**5)** [164]Managed Flood Releases Approach (incl. socio-economic links)	[164]Acreman *et al.*, 2000
[f]**Slovenia**	**1)** Hydrological methods (unspecified) **5)** Ecological methods (unspecified)	Smolar-Zvanut & Vrhovsek, 2002
[c]**South Africa**	**1)** [62]**Desktop Estimate**; [63]**Rapid (Reserve) Determination**; [33]FDC percentiles; [44]RVA (primarily IHA, *indices for semi-arid regions); [45]VHI; #[64]BWE; *[5]Ecotype-based Modified Tennant Method **3)** [89]IFIM; [118]MTA; *[111]2-D/3-D hydrodynamic modelling; *[112]Biotope-level modelling **4)** [148]**BBM (incl. CRD framework**, IFR Operating Rule Model, WRYM, FSR Method); [149]**Abbreviated BBM (incl. IRD** framework, FSR Method); [150]**DRIFT** (incl. framework for CRD); [152]Environmental Flow Management Plan Method; *Adapted BBM-DRIFT (assistance in development, but not applied locally); *[158]Benchmarking Methodology; *[159]FLOWRESM; *Combined	[164]Heeg & Breen, 1982 (& refs. cited: Phélines *et al.*, 1973; Bruton & Cooper, 1980); [45]Roberts, 1983; [219]O'Keeffe *et al.*, 1987; [33,148]Ferrar, 1989; King & O'Keeffe, 1989; [199,219]O'Keeffe & Davies, 1991; [89]Gore & King, 1989; [89]Gore *et al.*, 1990; [148]Arthington *et al.*, 1992; [89,148,189]King & Tharme, 1994; [64]Ractliffe & King, 1996; [33,148,118]Tharme, 1996, [44]1997, [5,111,112,158,159]unpubl. report; [152]Muller, unpubl. reports 1996, 1997; [167]O'Keeffe *et al.*, 1996; [148]Rogers & Bestbier, 1997; [148]Hughes *et al.*, 1997; [148]Hughes & Ziervogel, 1998; [148]King & Louw, 1998; [112,148]Tharme & King, 1998; [189]Wadeson & Rowntree, 1998; [220]Jewitt *et al.*, 1998, [44]unpubl. paper, 1999; Palmer, 1999; [33,44,62,63,64,89,118,148,149,150,152,164]King *et al.*, 1999, [62,63,148,149,150]2000, [150]this issue; [148]Hughes, 1999; [62,63,148,149]DWAF, 1999d, e;

	BBM/DRIFT **5)** [164]Managed Flood Releases Approach (incl. socio-economic links); [189]Physical Biotopes/Flow Types approaches; [167]Ecohydrological Models; [#199]KNP Consumptive/Non-Consumptive Approach **6)** [#219]River Conservation System (expert system); Direct use of hydrological & water quality data with various biotic indices; s PJ; *[220]Abiotic-Biotic Links Model	[150]Brown *et al.*, unpubl. report, 2000; [150]Brown & King, unpubl. report, 2000, 2002; [150]Metsi Consultants, 2000; [164]Acreman *et al.*, 2000; [44]Taylor *et al.*, unpubl. paper, 2001; [148]DWAF, pers. comm., 2001; [62,63]Hughes, 2001 (& refs. cited: [62]Hughes *et al.*, 1998; [62]Hughes & Münster, 1999); [148]O'Keeffe *et al.*, 2001; [189]King & Schael, 2001; [148]O'Keeffe & Hughes, unpubl. abs., 2002; [164]Poultney *et al.*, unpubl. abs., 2002; pers. comm: J. King; J. O'Keeffe; H. MacKay; G. Jewitt; V. Taylor; D. Grobler
[f]**Spain**	**1)** [10]**10% MAF**; [15]50 litres s^{-1}or [34,46]one of three other hydrological formulae based on Q_{347}; [49]Basic Flow Method (Q_b range: 5–50% MAF); Texas Method; Modified Tennant Method; [13]33–46% MAF; VHI **3)** [89]**IFIM**; [104]Cubillo Method; [105]Fleckinger Approach; [107]Integration of IFIM/PHABSIM with habitat quality classification (fisheries biomass) using multivariate statistical models **5)** [173]Basque Method; *[181]Combination of IFIM & elements of holistic methodologies **6)** [216]Multivariate biomass models	[104,105]Cubillo, 1992; [10,13,173]Docampo & De Bikuña, 1993 (& refs. cited: [15,34,46]CHNE, 1987); [89]García de Jalón *et al.*, 1994, cited in Dunbar *et al.*, 1998; [49]Palau & Alcazar, 1996; Alves *et al.*, 1996; [107,181,216]Dunbar *et al.*, 1998; [89] García de Jalón, unpubl. abs., 2002
[b]**Sri Lanka**	**4)** *Holistic methodologies **5)** [164]Managed Flood Releases Approach (incl. sediment flushing, disease vector control & socio-economic links) **6)** [202]PJ	[202]Matsuno *et al.*, 1998; [164]Acreman *et al.*, 2000; pers. comm: F. Amerasinghe; W. van der Hoek
[c]**Swaziland**	**4)** [148]BBM (incl. social & economic links)	[148]AfriDev/Knight Piesold Joint Venture & JTK Associates, 1999; [148]M. Chutter, pers. comm.
[f]**Sweden**	**1)** VHI? **3)** [99]**RSS**	[99]Alfredsen, 1998
[f]**Switzerland**	**1)** [15]Minimum Q of 50 litres s^{-1}or [34]Q_{347} (with minimum depth $= 0.20$ m, for $Q > 50$ litres s^{-1}); [45]VHI **3)** [97]CASIMIR **5)** *[181]Combination of IFIM-type models with elements of holistic methodologies (incl. floodplain ecological data) **6)** PJ; [221]Dilution Ratio-based Method (unspecified)	Hainard *et al.*, 1987, cited in Docampo & De Bikuña, 1993; [15,34]Docampo & De Bikuña, 1993; [221]Bernadová, 1998; [45,181]Dunbar *et al.*, 1998; [97]Schneider & Peter, unpubl. abs., 1999; [97]Jorde *et al.*, 2000, [97]2001; [97]Bratrich & Truffer, 2001; [97]Moosmann *et al.*, 2002; K. Jorde, pers. comm.
[b]**Taiwan**	**1)** [29]$\mathbf{Q_{95}}$ **3)** [90]PHABSIM component of IFIM **4)** *Holistic methodologies (BBM & DRIFT)	pers. comm: [90]S. Nakamura; [29]J. King
[c]**Tanzania**	**4)** *Holistic methodologies (incl. socio-economic analysis)	Sarunday, unpubl. abs., 2002; J. King, pers. comm.
[f]**Turkey**	**5)** [204]Scenario-based analysis (incl. SLURP Hydrological Model & PJ)	[204]IWMI & GDRS-T, 2000; W. van der Hoek, pers. comm.

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Appendix I. *Continued*

Country	Environmental flow methodologies	References for case studies
[f]**Ukraine**	**5)** [177]Delft Hydraulics Framework Analysis (incl. HEP, HSI, water quality, habitat modelling)	[177]De Vries, 1996; [177]Dunbar *et al.*, 1998
[f]**United Kingdom (England, Wales, Scotland, Northern Ireland) & Republic of Ireland**	**1)** [29]$\mathbf{Q_{95}}$ (DWF, or proportion or multiple thereof e.g.1.0 × DWF for sensitive rivers or 0.5 × DWF for least sensitive rivers, calculated using MICRO LOW FLOW/other programs; [32]Q_{98} (for less sensitive rivers, versus Q_{95}); [24]Q_{90}; [21]**MAM(7)** (DWF, or proportion thereof, MICRO LOW FLOW/other programs); [34]$\mathbf{Q_{347}}$ (considered equivalent to Q_{95}); [30]Welsh Water Authority Procedure (based on Q_{95}); [28]NGPRP Method; [61]Orth & Leonard Regionalization Method; [59]Flow Recession Approach; [45]VHI (notably low flow statistics); *[5]Ecotype-based Modified Tennant Method; *[52]Hoppe & Finnell Method; *[50]Texas Method (on ecotype basis); *[41]Regionalization of seasonal FDCs for river ecotypes; *[44]RVA (for England, & particularly Scotland, with modifications) **2)** [67]Wetted Bed Area-Flow Method; *[66]R-2 Cross Method (for Wales & Scotland, particularly) **3)** [89]**IFIM** (*incl. habitat-biomass/population relationships, mesohabitat/biotope HSI curves & modelling); *[97]CASIMIR; *[106]Linked statistical hydraulic & multivariate habitat use models **4)** [162]River Babingley (Wissey) Method (incl. various eco-hydrological models/methods to determine benchmark flows for EAFR, e.g. PHABSIM & FDC analyses); *[147]Holistic Approach; *[148]BBM; *[153]EPAM **5)** [189]Physical Biotopes/Functional Habitats approaches; [155]Expert panel studies (unspecified); [201]DSHHP Method (associated with SWALP); [192]holistic elements based on natural flow regime; *[181]Combination of IFIM/PHABSIM analyses for target species with holistic elements; *[173]Basque Method; *[181]IFIM in association with other flow regime elements; *[198]Regionalization methods based on habitat modelling **6)** [202]PJ; [217]RIVPACS (incl. *additional development, e.g. flow-related variables & species responses); [222]Habitat Attribute-BMWP Model; [218]LIFE Method; [205]SWK Method; [209]Direct use of fisheries population data (incl. migration & spawning activities—Ireland); [223]Fish Management Models; *[206]Jones & *Peters Method; [207]HABSCORE (with additional developments); *[224]Regional regression-based models (unspecified, with additional developments); *[210]Analysis of raw population data under alternative river management procedures	[202]Sheail, 1984, 1987; [21,29,89,223]Bullock *et al.*, 1991 (& refs. cited; [29]Drake & Sherriff, 1987); [21,29]Gustard & Bullock, 1991; Petts & Maddock, 1994; [89]Johnson *et al.*, 1995; [89]Elliott *et al.*, 1996; [217]Wright *et al.*, 1996; [189]Padmore, 1998; [5,21,28,30,34,44,50,52,66,89,97,106,147,148,153,173,181,189,198,201,206,207,209,210,217,224]Dunbar *et al.*, 1998 (& refs. cited: [34,41,45]Gustard *et al.*, 1987; [217]Brown *et al.*, 1991; [223]Lawson *et al.*, 1991; [41]Bullock *et al.*, 1994; [89]Bird, 1996; [41]Young *et al.*, 1996; Hardy, 1996; O'Grady, 1996; [155]Ibbotson, 1996; Acreman & Adams, 1997); [89]Gustard & Cole, 1998; [89]Gustard & Elliott, 1998 (& refs. cited: [89]Johnson *et al.*, 1993a, b; [162]Petts & Bickerton, 1994; Maddock & Petts, 1995); [29,59,61,67,222]Petts *et al.*, 1995; [162]Petts, 1996; [162]Petts *et al.*, 1999 (& refs. cited: [29]Gustard, 1989; NRA, 1995, 1996); [21,24,29,44,147]Bragg *et al.*, 1999 (& refs. cited: [162]Evans, 1997; [32]Kirmond & Barker, 1997); [218,205]Extence *et al.*, 1999 (& refs. cited: [206]Jones & Peters, 1977; [205]SWK, 1992); [89]Spence & Hickley, 2000; [89,181]Gibbins & Acornley, 2000; [29,218]Dunbar *et al.*, unpubl. paper, 2002; [29,192]Sambrook & Petts, unpubl. abs., 2002; [217]Tharme, unpubl. report.

[d]**United States of America (incl. Alaska)**	**1)** [1]**Tennant Method** (with regional adjustments for local hydrological regimes, inclusion of fish periodicity data, flow duration, QAM); [2]Tessman Modification of Tennant Method; [3]Bayha Modification of Tennant Method; [12]30% MAF; [47]**(New England) ABF Method** (or [47]Constant Yield Method); [48]Refined ABF Method; [37]**7Q10**; [19]Median Monthly Flow; [16]QAM; [50]Texas Method; [51]O'Shea Hydrological/ Watershed Characteristics Method; [33]FDC percentiles; [44]**RVA** (primarily IHA, incl. relationships between indices & biotic responses); [28]NGPRP/Q_{90} Method; [#54]September Median Flow Method; [61]Orth & Leonard Regionalization Method; [#55]Robinson Method; [#56]Washington Base Flow Methodology; [52]Hoppe & Finnell Method; VHI **2)** [65]**Wetted Perimeter Method** (with various % reductions in wetted perimeter); [66]**R-2 Cross Method** (primarily R-2 Cross Hydraulic Model); [76]USGS Toe-Width Method; [77]Arkansas Method; [78]Oregon Method; [79]Vermont Fish-Flow Method; [74]Standard Depth Approach; [#72]Curtis & Hooper Approach; [#80]Pearson *et al.* Approach; [#81]Hoppe Limiting Factor-Transect Approach; [#82]Hoppe's 1975 Method; [#83]Collings' Methodology; [#84]USFS Region 2/Critical Area Method; [#85]Rantz Regression Equation Method; [#86]Average Stream Width/One Flow Method; [87]US Fisheries Service Personnel Region 4 Method; [70]Colorado Method; [71]Colorado Division of Wildlife Method; [75]Simplified staff-gauge analysis (with various limiting habitat criteria) **3)** [89]**IFIM** (primarily PHABSIM, incl. 2D hydrodynamic modelling, 2D habitat metrics in Windows environment; habitat duration curves & time series); [115]Integration of IFIM with population response (/hydrologic/water quality) models; [96]**RHABSIM**; [118]**MTA**; [101]**RCHARC**; [94]mesoHABSIM Model; [97]CASIMIR; [140]WSP Hydraulic Model (with PJ); [142]HEC-2 Hydraulic Model (with PJ); [141]AVDEPTH Hydraulic Model (with PJ); [#120]Resting Microhabitat Analysis; [#121]Subjective Cover Rating Method; [#132]Wesche's Cover Rating System; [#122]Banks *et al.* Approach; [#123]California Pit River Approach; [#124]White's Methodology (incl. WSP Hydraulic Model); [#125]Thompson's Methodology; [#126]Usable Width Method; [#128]Oregon UW Method; [#127]Weighted UW Method (incl. Average Velocity Analysis); [#139]Critical Area-Indicator Species Methodology (incl. Contour Hydraulic Model); [#129]Idaho Method; [#130]USFWS Method; [#131]WRRI Cover Method; [#133]Washington Dept. Fisheries Method; [#134]USFS Region 6 (R-6) Method; [#135]USFS Region 4 Method; [#136]West Virginia Method; [#137]Connecticut River Basin Method; [#138]Waters' Methodology	Elser, 1972; [65]Bartschi, 1976; [1,28,33,55,56,66,120,121,130,132]Stalnaker & Arnette, 1976 (& refs. cited: [65,72]Curtis, 1959; [86,126,127]Sams & Pearson, 1963; [85]Rantz, 1964; [87]Herrington & Dunham, 1967; Robinson, 1969; [80]Pearson *et al.*, 1970; [52]Hoppe & Finnell 1970, 1973; [125,126]Thompson, [83]1972, 1974; [131]Wesche, 1973; [65,72]Hooper, 1973; [133]Bishop & Scott, 1973; [84]Anon, 1973; [66]Anon, 1974; [133]Collings, 1972, [65,83]1974; [122]Banks *et al.*, 1974; [139]Bovee, 1974; [81,82]Hoppe 1975; [87]Dunham & Collotzi, 1975; [123]Waters, 1975; White, [118,128]1975, [129,140]1976; [129]White & Cochnauer, 1975; [66,84]US Forest Service); [70]Russell & Mulvaney, 1973, cited in Growns & Kotlash, 1994; [134]Swank, 1975, cited in Kinhill Engineers, 1988; [1]Tennant, 1976; [138]Waters, 1976; [1,140]Elser, 1976; [66,140,142]Bovee & Milhous, 1978; [139]Bovee *et al.*, 1978; [37]Stalnaker, 1979; [178]Binns & Eiserman, 1979; [1,28,70,75,82,86,128,129,131,133,134]Wesche & Rechard, 1980; [74]Colorado Division of Wildlife, cited in Prewitt & Carlson, 1980; [1,65,66,74,83,120,140,141]Prewitt & Carlson, 1980; [65]Nelson, 1980; [1,89,118]Orth & Maughan, 1981; [1]Newcombe, 1981; [89]Sale *et al.*, 1981, cited in Locke, 1996; [28,33,47]Loar & Sale, 1981; [37,89]Bovee, 1982; [1,71]Annear & Conder, 1984; [180]Williams & McKellar, 1984; [89]Cavendish & Duncan, 1986; [139]Loar *et al.*, 1986; [89]Orth, 1987; Gore & Nestler, 1988; [1,37,47,54,65,76,77,78,79,89,141]Reiser *et al.*, 1989a; [89,141]Milhous *et al.*, 1989; [184]Singh & Broeren, 1989; [89]Gore, 1989, 1998; [89]Gore *et al.*, 1989; [1,37,61]Orth & Leonard, 1990; [47]Kulik, 1990; [171]Jourdonnais *et al.*, 1990 (& refs. cited: [171]Bain *et al.*, 1986; [171]Hall *et al.*, 1989); [89]Armour & Taylor, 1991; [50]Matthews & Bao, 1991; [170]Hill *et al.*, 1991; [28,33,37]Caissie & El-Jabi, 1994 (& refs. cited: [28]NGPRP 1974; [19,47]USFWS, 1981; [12,89]Annear & Conder, 1983); Swank, 1975, cited in Growns & Kotlash, 1994; [115]Cheslak & Jacobsen, 1990 [142]Gordon *et al.*, 1992; [89]Stalnaker *et al.*, 1994; [101]Nestler *et al.*, 1994, cited in Richter *et al.*, 1997; [51]O'Shea, 1995; [47]Karim *et al.*, 1995 (& refs. cited: Wesche, 1976); [1]Estes, 1996; [89]Tharme, 1996; Gippel & Stewardson, 1998 (& refs. cited: [65]Cochnauer, 1976; [65]Nelson, 1980; [65]Filipek *et al.*, 1987); [191]Stanford *et al.*, 1996; [101]Nestler *et al.*, 1996; [89]Ghanem *et al.*, 1996; [1,44,170]Richter *et al.*, 1996, 1997; [89]Stalnaker, 1998; [1,65,66,89]Espegren, 1998 (& refs. cited: [66,71]Nehring, 1979; US Fish & Wildlife Service, 1981; [66]Espegren, 1996); [89]Waddle, 1998a, b; [89]Milhous, 1998a, b; [2,3,135,136,137,176,178]Dunbar *et al.* 1998 (& references cited: [184]Singh, 1993; [1,37]Caissie, 1995; USFS); [165]King *et al.*, 1999; [94,192]Anon, 2001; [96]Payne & Associates web site, 2000; [94]IHP/DNR, Cornell University web site, 2001; [97]Clayton, 2002; pers. comm: T. Boyle; R. Milhous; B. Richter; T. Waddle; J. Bartholow; C. Estes; [94]P. Parasiewicz; [97]K. Jorde

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Appendix I. *Continued*

Country	Environmental flow methodologies	References for case studies
	5) [170]Hill, Platts & Beschta Methodology; [165]Experimental Flood Release Approach (e.g. Colorado River); [171]Multiattribute Tradeoff Analysis; [180]Energy Analysis; [184]Singh Regionalization Method; [176]HEP; [192]Holistic elements based on natural flow regime (e.g. Missouri River 'spring rise/split navigation season' *flow plan); [178]HQI Method; [191]Restructuring of altered flow regimes **6)** PJ	
[c]Zambia	**5)** [164]Managed Flood Releases Approach	[164]Acreman *et al.*, 2000
[c]Zimbabwe	**4)** [151]Adapted BBM-DRIFT **6)** [202]PJ	[202]P. Macy, pers. comm., cited in Brown & King, unpubl. report, 1999; [151]Steward *et al.*, unpubl. paper, 2002

Abbreviations

1D/2D/3D—one/two or three-dimensional (hydrodynamic modelling); 7Q10—the minimum average 7-day (consecutive) flow expected to occur once every 10 years; AAF—Average Annual Flow (= MAF); ABF—Average Base Flow/Aquatic Base Flow; BBM—Building Block Methodology; BENHFOR—Benthic Habitat For Optimum Flow Reckoning; BFI—Base Flow Index; BMWP—Biological Monitoring Working Party (score); BSP—Biologically Significant Period; BWE—Bulk Water Estimate; CASIMIR—Computer Aided Simulation Model for Instream flow Requirements in regulated/diverted streams; CHNE—Confederación Hidrográfica del Norte de España; CRD—Comprehensive (Reserve) Determination; CWPR—Centre for Water Policy Research; DNR—Department of Natural Resources; DRIFT—Downstream Response to Imposed Flow Transformations; DSHHP—Drake, Sherriff/Howard Humphreys & Partners; DWAF—Department of Water Affairs and Forestry; DWF—Dry Weather Flow; DWR—Department of Water Resources; EAFR—Ecologically Acceptable Flow Regime; EFM—Environmental flow methodology; EFR—Environmental flow requirement; EVHA—Evaluation of Habitat Method; EPAM—Expert Panel Assessment Method; FDC—Flow Duration Curve; FSR Method—Flow Stress or Response Method; FST—Fliesswasserstammtisch; GIS—Geographical Information System; GDRS-T—General Directorate of Rural Services, Turkey; HDC—Habitat Duration Curve; HEP—Habitat Evaluation Procedure; HSI—Habitat Suitability Index; IHA—Indices of Hydrologic Alteration; IHP—Instream Habitat Program; IFIM—Instream Flow Incremental Methodology; IFR—Instream Flow Requirement; incl.—including; IQQM—Integrated Quantity Quality Model for hydrological modelling; IRD—Intermediate (Reserve) Determination; IWMI—International Water Management Institute; KNP—Kruger National Park (South Africa); LIFE—Lotic-invertebrate Index for Flow Evaluation; MAF—Mean Annual Flow (= AAF); MAM(7)—mean annual minimum 7-day flow frequency statistic; MQ—Mean Discharge? (unspecified in source reference); MAR—Mean Annual Runoff (= AAF); MNQ—Median Discharge? (unspecified in source reference); Mean Q_{min}—mean of annual 1-day minimum daily flows over the period of record; Median Q_{min} (or Median Minimum) = median of annual 1-day minimum daily flows over the period of record; MTA—Multiple Transect Analysis; MWD—Ministry of Works and Development; NGPRP—Northern Great Plains Resource Program; NPF—Normality Preservation Flow; NRA—National River Authority; OCFR—Obligated Conservation Flow Release; PAWN—Policy Analysis Water Management of the Netherlands; PHABSIM—Physical Habitat Simulation Model; PJ—(case-specific) professional judgement; Q—discharge; Q_{90}, Q_{95}, Q_{50}, Q_n—discharge equalled or exceeded 90%, 95%, 50% (= Median Monthly Flow), n% of the time, based on FDC analysis; Q_{347} or Q_{347d} (equivalent to Q_{95}; Dunbar *et al.*, 1998) and $Q_{355(d)}$, $Q_{364(d)}$, etc.—discharge equalled or exceeded for the specified number of days per year; QAM—Mean Monthly Flow; RVA—Range of Variability Approach; refs.—references; RHABSIM—Riverine Habitat Simulation Program; RHYHABSIM—River Hydraulics and Habitat Simulation Program; RIMOS—River Modelling System; RSS—River System Simulator; RCHARC—Riverine Community Habitat Assessment and Restoration Concept; RIVPACS—River Invertebrate Prediction and Classification System, UK; SGCMC—Snowy Genoa Catchment Management Committee; SLURP—Semi-distributed Land Use-based Runoff Processes; SREP—Snowy River Expert Panel; SWALP—Surface Water Abstraction Licencing Policy; SWI—Snowy Water Inquiry; SWK—Scott Wilson Kirkpatrick; TAP—Technical Advisory Panel; USFS—United States Forest Service; USFWS—United States Fish and Wildlife Service; USGS—United States Geological Survey; UW—Usable Width; VHI—various simple hydrological indices (unspecified, in addition to any specific flow indices listed); WAMP—Water Allocation and Management Planning; WRD—water resource development; WRRI—Water Resources Research Institute; WRYM—Water Resources Yield Model; WSP—Water Surface Profile.

Appendix II. Summary of select holistic environmental flow methodologies (EFMs) applied globally, highlighting salient features, strengths and limitations, as well as their current status in terms of development and application. Select references are provided for each methodology, with additional supporting references and abbreviations listed in Table II. EFMs are presented in no particular order (EF, environmental flow: EFA, EF assessment; EFR, EF requirement)

Methodology (key references)	Origins	Main features, strengths and limitations	Status
Benchmarking Methodology (DNR, 1998b, cited in Arthington, 1998a; Brizga, 2000)	Developed in Queensland, Australia, by numerous local researchers & DNR, to provide a framework for assessing risk of environmental impacts due to WRD, at basin scale	Comprehensive, scenario-based, top-down approach for application at a whole-of-basin scale, using field & desktop data for multiple river sites; EFM has 4 main stages—(1) establishment: formation of multidisciplinary expert panel (TAP) & development of hydrological model, (2) ecological condition & trend assessment: development of spatial reference framework, assessment of ecological condition for suite of ecosystem components (using 5-point rating of degree of change from reference condition & appropriate methods for each component), development of generic models defining links between flow regime components & ecological processes, selection of key flow indicators with relevance to these relationships, modelling-based assessment of hydrological impacts, (3) development of an EF risk assessment framework: models are developed for all/some key flow indicators showing levels of risk of ecological/geomorphological impacts associated with different degrees of flow regime change, risk levels are defined by association with benchmark sites which have undergone different degrees of flow-related change in condition, link models are used to show how the modelled flow indicators affect ecological condition, (4) evaluation of future WRD scenarios, using risk assessment & link models, ecological implications of scenarios & associated levels of risk readily expressed in graphical form; EFM is particularly suited to data poor situations; potential for use in developing countries context & for application to other aquatic ecosystems; utilises a wide range of specialist expertise; presents a comprehensive benchmarking process; provides several ways of developing risk assessment models, guidance on key criteria for assessing condition, & key hydrological & performance indicators; recent approach built on several preceding EFA initiatives; no explicit consideration of social component, but with scope for inclusion; requires evaluation of several aspects (e.g. applicability/sensitivity of key flow statistics, degree to which benchmarks from other basins/sites are valid considering differences in river hydrology & biota)	Sole holistic EFM for basin-scale EFAs; adopted as standard EFM in Queensland's WRD planning framework; applications in 8 basins; only applied in Australia to date
Holistic Approach (Arthington, 1998a & cited references: Arthington *et al.*, 1992b; Arthington, 1994; Davies *et al.*, 1996; Growns & Growns, 1997)	Developed in Australia to address the flow requirements of the entire riverine ecosystem; shared conceptual basis with BBM	Loosely structured set of methods for bottom-up construction of EF regime, with no explicit output format; principally represents a flexible conceptual framework, elements of which have been adapted in a variety of ways for individual studies; lack of structured set of procedures & clear identity for EFM hinders rigorous routine application; basic tenets & assumptions as per BBM; systematic construction of a modified flow regime, on a monthly-by-month & flow element-by-element basis, to achieve predetermined objectives for future river condition; incorporates more detailed assessment of flow variability than early BBM studies; includes method for generating tradeoff curves for examining alternative water use scenarios; some risk of inadvertent omission of critical flow events; represents the theoretical basis for most other holistic EFMs	Represents conceptual basis of most other holistic EFMs; applied in various forms in Australia

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Appendix II. *Continued*

Methodology (key references)	Origins	Main features, strengths and limitations	Status
Building Block Methodology (BBM) (King & Tharme, 1994; Tharme & King, 1998; King & Louw, 1998; King *et al.*, 2000)	Developed in South Africa by local researchers & DWAF, through application in numerous WRD projects to address EFRs for entire riverine ecosystems under conditions of variable resources; adapted for determination of the ecological Reserve under new Water Law	Rigorous & extensively documented (manual available); prescriptive bottom-up approach; moderate to highly resource intensive; developed to differing extents for both intermediate-level (2 months) or comprehensive (1–2 years) EFAs, within Reserve framework; based on a number of sites within representative/critical river reaches; includes a well established social component (dependent livelihoods); functions in data poor/rich situations; comprises 3-phase approach—(1) preparation for workshop, including stakeholder consultation, desktop & field studies for site selection, geomorphological reach analysis, river habitat integrity & social surveys, objectives setting for future river condition, assessment of river importance & ecological condition, hydrological & hydraulic analyses, (2) multidisciplinary workshop-based construction of modified flow regime through identification of ecologically essential flow features on a month-by-month (or shorter time scale), flow element-by-flow element basis, for maintenance & drought years, based on best available scientific data, (3) linking of EFR with WRD engineering phase, through scenario modelling & hydrological yield analysis; EFM exhibits limited potential for examination of alternative scenarios relative to DRIFT, as BBM EF regime is designed to achieve a specific predefined river condition; incorporates a monitoring programme; some risk of inadvertent omission of critical flow events; high potential for application to other aquatic ecosystems; links to external stakeholder/public participation processes; flexible & amenable to simplification for more rapid assessments; less time, cost & resource intensive than DRIFT; shared conceptual basis with Holistic Approach; applicable to regulated/unregulated rivers, & in flow restoration context; FSR Method under development to facilitate scenario-based assessment of alternative flow regimes	Most frequently used holistic EFM globally, applied in 3 countries; adopted as the standard South African EFM for Reserve determinations
Downstream Response to Imposed Flow Transformations Process (DRIFT) (Metsi Consultants, 2000; King *et al.*, this issue)	Developed in southern Africa by Southern Waters & Metsi Consultants (with inputs from Australian & southern African researchers) to address the need for an interactive scenario-based holistic EFM with an explicit socio-economic component	Appropriate for comprehensive EFAs (1–3 years) based on several sites within representative/critical river reaches; flexible, interactive, top-down, scenario-based process comprised of 4 modules—(1) biophysical module: used to describe present ecosystem condition, to predict how it will change under a range of different flow alterations for synthesis in a database, uses generic lists of links to flow & relevance for each specialist component, direction & severity of change are recorded to quantify each flow-related impact, (2) sociological module: used to identify subsistence users at risk from flow alterations & to quantify their links with the river in terms of natural resource use & health profiles, (3) scenario development module: links first 2 modules through querying of database, to extract predicted consequences of altered flows (with potential for presentation at several levels of resolution) used to create flow scenarios (typically 4 or 5), (4) economic module: generates description of costs of mitigation & compensation for each scenario; EFM modules require refinement; well developed ability to address socio-economic links to ecosystem; considerable scope for comparative evaluation of alternative modified flow regimes; resource intensive, high potential for application to other aquatic ecosystems; amenable to simplification for more rapid assessments; well documented; uses many successful features of other holistic EFMs; same conceptual basis as BBM & Holistic Approach; exhibits parallels with benchmarking approaches; output is more suitable for negotiation of tradeoffs than in BBM/other bottom-up approaches, as implications of not meeting the EFR are readily accessible; links to external public participation process &	EFM with most developed capabilities for scenario analysis & explicit consideration of social & economic effects of changing river condition on subsistence users; limited application to date, within southern Africa

		macro-economic assessment; generic lists provide clear parameters for inclusion in a monitoring programme; approach provides limited consideration of synergistic interactions among different flow events; limited inclusion of flow indices describing system variability; applicable to regulated/unregulated rivers & for flow restoration	
Adapted BBM-DRIFT Methodology (Steward *et al.*, 2002)	Developed in Zimbabwe by Mott MacDonald Ltd. in collaboration with Zimbabwe National Water Authority (with input from South Africa) through adaptation of key elements of BBM & DRIFT, in response to requirements in new Water Act for EFAs	Simplified top-down, multidisciplinary team approach, for use in highly resource-limited (including data) situations & with direct dependencies by rural people on riverine ecosystems; combines pre-workshop data collection phase of BBM with DRIFT's scenario-based workshop process; comprises 3 phases—(1) preparation for workshop as per BBM/DRIFT, but excluding certain components (e.g. habitat integrity & geomorphological reach analyses) & with limited field data collection, (2) workshop, with simplified DRIFT process linking the main geomorphological, ecological & social impacts with elements of the flow regime (based on assessments of impact & severity for component-specific generic lists), used to construct a matrix, (3) use of matrix in evaluating development options, where the matrix indicates ecosystem aspects that are especially vulnerable/important to rural livelihoods, socially & ecologically critical elements of the flow regime & EF recommendations for mitigation; EFM incorporates more limited ecological & geomophological assessments than BBM/DRIFT; limited coverage of key specialist disciplines; no link to system for defining target river condition; especially appropriate in developing countries context; requires further development & validation; would benefit from inclusion of economic data	Under early development, single documented application to date
Flow Events Method (FEM) (Stewardson, 2001; Cottingham *et al.*, 2001)	Developed by Australian Cooperative Research Centre for Catchment Hydrology to provide state agencies with a standard approach for EFAs	Top-down method for regulated rivers; considers the maximum change in river hydrology from natural for key ecologically relevant flow events, based on empirical data or expert judgement; considered a method of integrating existing analytical techniques & expert opinion to identify important aspects of the flow regime; EFM comprises 4 steps—(1) identification of ecological processes (hydraulic, geomorphic & ecological) affected by flow variations at range of spatial & temporal scales, (2) characterisation of flow events (e.g. duration, magnitude) using hydraulic & hydrological analyses, (3) description of the sequence of flow events for particular processes, using a frequency analysis to derive event recurrence intervals for a range of event magnitudes, (4) setting of EF targets, by minimising changes in event recurrence intervals from natural/reference or to satisfy some constraint (e.g. maximum % permissable change in recurrence interval for any given event magnitude); EFM's singular development appears to be analysis of changes in event recurrence intervals with altered flow regimes; draws greatly on established procedures of other complex EFMs (e.g. BBM, FLOWRESM, & DRIFT); may be used to (1) assess the ecological impact of changes in flow regimes, (2) specify EF management rules/targets, (3) optimise flow management rules to maximise ecological benefits within constraints of existing WRD schemes; possibly places undue emphasis on frequency compared with other event characteristics; no social component; requires additional validation; incorporated within various expert-panel/other assessment frameworks	Recent approach with few applications in Australia to date; often linked to expert-panel approaches

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Appendix II. *Continued*

Methodology (key references)	Origins	Main features, strengths and limitations	Status
Flow Restoration Methodology (FLOWRESM) (Arthington, 1998a; Arthington *et al*., 2000)	Developed in a study of the Brisbane River, Queensland, Australia, for specifically addressing EFRs in river systems exhibiting a long history of flow regulation & requiring restoration	Primarily bottom-up, field & desktop approach appropriate for comprehensive (or intermediate) EFAs; designed for use in intensively regulated rivers; emphasis is on identification of the essential features that need to be built back into the hydrological regime to shift the regulated river system towards the pre-regulation state; EFM uses an 11-step process in 2 stages, in which the following are achieved—(1) review of changes to the river hydrological regime (focusing on unregulated, present day & future demand scenarios), (2) series of steps within scenario-based workshop, using extensive multidisciplinary specialist input: determination of flow-related environmental effects, rationale & potential for restoration of various flow components so as to restore ecological functions, & establishment of EFRS based on identification of critical flow thresholds/flow bands that meet specified ecological/other objectives, (3) assess implications of multiple scenarios for system yield, (4) outline remedial actions not related to flow regulation, (5) outline monitoring strategy to assess benefits of EFRs; EFM includes well developed hydrological & ecological modelling tools; represents a hybrid of the Holistic Approach & BBM; more rigorous than expert-panel methods (e.g. SPAM); some risk of inadvertent omission of critical flow events; includes flexible top-down process for assessing ecological implications of alternative modified flow regimes; potential for adoption of full benchmarking process to rank outcomes of not restoring critical flows; requires documentation of the generic procedure for wider application	Most comprehensive EFM for flow-related river restoration; probably only a single application in Australia to date
River Babingley (Wissey) Method (Petts *et al*., 1999 & cited references: Petts, 1996; Petts & Bickerton, 1994)	First developed for application in groundwater-dominated rivers, Anglian Region of England	Bottom-up field & desktop approach; EAFR (EF regime) defined in 4 stages—(1) ecological assessment of river & specification of an ecological objective comprising specific targets (for river components & biota), (2) determination of 4 general & 2 flood benchmark flows to meet the specified targets, (3) use of flows to construct 'ecologically acceptable hydrographs', which may include provision for wet years & drought conditions, (4) assignment of acceptable flow frequencies & durations to the hydrographs, & their synthesis into a flow duration curve, the EAFR; EFM uses hydro-ecological models, habitat & hydrological simulation tools to assist in identification of benchmark flows & overall EAFR; allows for flexible examination of alternative EF scenarios; loosely structured approach, with limited explanation of procedures for integration of multidisciplinary input; risk of omission of critical flow events from EAFR; specific to baseflow-dominated rivers & requires further research for use in flashy catchments	Relatively limited application to date; general approach appears to have been extended to other EFA studies in the UK
Habitat Analysis Method (Walter *et al*., 1994; Burgess & Vanderbyl, 1996; Burgess & Thoms, 1997, cited in Arthington 1998a; Burgess & Thoms, 1998; Arthington, 1998a)	Developed by former Queensland Department of Primary Industries, Water Resources (now DNR), Australia, as part of WAMP initiative	Relatively rapid, inexpensive, basin-wide reconnaissance method for determining preliminary EFRs at multiple points in catchment (rather than at a few critical sites); superior to simple hydrological EFMs, but inadequate for comprehensive EFAs; field data limited/absent; bottom-up process of 4 stages using TAP—(1) identification of generic aquatic habitat types existing within the catchment, (2) determination of flow-related ecological requirements of each habitat (as surrogate for EFRs for aquatic biota), using small group of key flow statistics, plus select 'biological trigger' flows & floods for maintenance of ecological/geomorphological processes, (3) development of bypass flow strategies to meet EFRs, (4) development of EFR monitoring strategy; EFM represents an extension of expert panel approaches (EPAM, SPAM), with conceptual basis & assumptions adapted from Holistic Approach; little consideration of specific flow needs of individual ecosystem components; requires standardization of process, refinement of flow bands linked to habitats & addition of flow events	Precursor of Benchmarking Methodology within WAMP initiatives; several applications within Australia

Environmental Flow Management Plan Method (FMP) (Muller, unpubl. report, 1996, 1997; DWAF, 1999d)	Developed in South Africa by the Institute for Water Research, for use for intensively regulated river systems	Simplified bottom-up approach, applicable in highly regulated & managed systems with considerable operational limitations; considered for use within South Africa Reserve determination process only where BBM or equivalent approach cannot be followed; workshop-based, multidisciplinary assessment including ecologists & system operators; 3-step process—(1) definition of operable reaches for study river & site selection, establishment of current operating rules, (2) determination of current ecological status & desired future state, (3) identification of EFRs using similar procedures to BBM; EFM has poorly established post-workshop scenario phase; limited scope for application; EFM structure & procedures for application are not formalised or well documented; no evaluation undertaken; considerably more limited approach than FLOWRESM	Limited to 3 applications; only used in South Africa to date; uncertain status within the national Reserve framework
Expert Panel Assessment Method (EPAM) (Swales *et al.*, 1994; Swales & Harris, 1995)	First multidisciplinary panel based EFM used in Australia, developed jointly by the New South Wales departments of Fisheries & Water Resources	Bottom-up, reconnaissance-level approach for initial assessment of proposed WRDs; rapid & inexpensive, with limited field data collection; site-specific focus; applicable primarily for sites where dam releases are possible; relies on field-based ecological interpretation, by a panel of experts, of different multiple trial flow releases (ranked in terms of scored ecological suitability) from dams, at one/few sites, to determine EFR (typically as flow percentiles); low resource intensity; limited resolution of EF output; aims to address river ecosystem health (using fish communities as indicators), rather than to assess multiple ecosystem components; based on same concepts as Holistic Approach & BBM; strongly reliant on professional judgement; limited subset of expertise represented by panel (e.g. fish, invertebrates, geomorphology); simplistic in terms of the range of ecological criteria & components assessed (but scope for inclusion of additional ones) & the focus on fish; no explicit guidelines for application; poor congruence in opinion of different panel members (e.g. due to subjective scoring approach, individual bias); requires further validation; led to development of more advanced, but similar SPAM, Snowy Inquiry Methodology & other expert panel approaches	Applied only in Australia; several applications, both in original & variously modified forms
Scientific Panel Assessment Method (SPAM) (Thoms *et al.*, 1996)	Developed during an EFA for the Barwon-Darling River System, Australia	Bottom-up field (multiple sites) & desktop approach appropriate for provision of interim or intermediate level EFAs; evolved from EPAM as more sophisticated & transparent expert-panel approach; aims to determine a modified flow regime that will maintain ecosystem health; differs from EPAM in that key features of the ecosystem & hydrological regime & their interactions at multiple sites are used as basis for EFA; EFR process includes—(1) identification of management performance criteria by panel of experts for 5 main ecosystem components: fish, trees, macrophytes, invertebrates & geomorphology, (2) application of the criteria for three elements (& associated descriptors) identified as exerting an influence on the ecosystem components (viz. flow regime, hydrograph & physical structure at 3 spatial scales), (3) workshop-based cross-tabulation approach to identify & document generalised responses/impacts for each ecosystem components to each specific descriptor (for each element), so as to relate flow regime attributes to ecosystem responses & EFRs; incorporates system hydrological variability & elements of ecosystem functioning; includes stakeholder-panel member workshop for EFR refinement; many conceptual features & methodological procedures in common with the Holistic Approach & BBM; well defined EFA objectives; some potential for inclusion of other ecosystem components; led to the evolution of other expert-panel approaches; limited use of field data; poor definition of output format for EFR; moderately rapid, flexible & resource-intensive; simpler, less quantitative supporting evidence, & less rigorous than FLOWRESM, BBM & DRIFT; no recent developments documented	Appears limited to a single application in Australia in original form; general approach variously modified for other expert panel EFAs