June 5, 2009

Transmittal to Basin and Bay Expert Science Teams (BBESTs)

Report # SAC-2009-03

Title: Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries, within the Context of the Senate Bill 3 Environmental Flows Process.

The attached document constitutes another deliverable from the Senate Bill 3 Science Advisory Committee (SAC) to assist the BBESTs in carrying out their responsibilities under the statute. This report addresses one of the principal mandates of the law, namely the establishment of an environmental flow regime to maintain a sound ecological environment in the estuarine systems on the Texas Coast. The complexity of this assignment is acknowledged at the outset, and the focus of the report is on applying existing available methodologies and data resources to successfully accomplish the task. The advice of the SAC is for you to recognize the need to simplify the approach as necessary, and to document the BBEST decision process along the way, realizing that the results will likely be imperfect.

The document presents a simplified conceptual model relating Inflow to "Biology", with Salinity as a keystone habitat attribute, as a likely approach that is reasonably achievable given the timeframe in which the current BBESTs must develop their recommendations. The document contains a concluding Section 6 which addresses realistic expectations and offers specific recommendations from the SAC at this point in the Senate Bill 3 process.

As in previous SAC deliverables, this document is characterized as a "Working Draft". Given the complexity of the estuarine environmental inflow regime determination, this characterization is particularly appropriate. We strongly encourage a healthy dialogue between the BBESTs and the SAC on the content of this document, which will surely result in improvements which will yield the best possible scientifically-based environmental flow recommendations. Finally, as always, the SAC offers this information as guidance and not prescription, and remains hopeful that the BBESTs will find this information useful in their deliberations. We look forward to your feedback as we undertake our respective responsibilities under Senate Bill 3.

Robert J. Huston, Chairman, SB3 Science Advisory Committee

*WORKING DRAFT*

# Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries

## Within the Context of the Senate Bill 3 Environmental Flows Process

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**Senate Bill 3 Science Advisory Committee**
**for Environmental Flows**

**Science Advisory Committee Members**

Robert J. Brandes, Ph.D., P.E., Vice-Chair
Franklin Heitmuller, Ph.D.
Robert Huston, Chair
Paul Jensen, Ph.D, P.E.
Mary Kelly
Fred Manhart
Paul Montagna, Ph.D
George Ward, Ph.D
James Wiersema

**Document Version Date: June 5, 2009**

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# SECTION 1
# INTRODUCTION

Environmental flows, which include flows in rivers and streams and freshwater inflows to bays and estuaries, have not been addressed uniformly in water development project planning and permitting in Texas. Senate Bill 3, passed by the Texas Legislature in 2007, set out a new regulatory approach to protect such flows through the use of environmental flow standards developed through Texas Commission on Environmental Quality (TCEQ) rulemaking. Senate Bill 3 directed the use of an environmental flow regime in developing flow standards and defined an environmental flow regime as a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats.

Each Basin and Bay Expert Science Team (BBEST) is charged with developing recommendations for both an instream flow regime and for a complete freshwater inflow regime to protect a "sound ecological environment" and to maintain the productivity, extent, and persistence of key aquatic habitats in bays and estuaries. Instream flow regime requirements have been addressed previously (SAC, 2009a),[1] by the Texas Environmental Flows Science Advisory Committee (SAC). The focus of this document is on bay and estuary inflows. This regime will have to be developed recognizing the inherent variability in weather and inflow conditions that have contributed to and sustained these productive estuarine ecosystems over time. Freshwater inflow serves a variety of important functions to coastal estuarine ecosystems by creating and preserving low-salinity nurseries, transporting sediments, nutrients, and organic matter downstream, and affecting estuarine species movements and reproductive timing (Longley 1994, Montagna et al. 2002; SAC, 2004).

This document provides background information and discussion of various methods that can be used to develop freshwater inflow recommendations for Texas bays and estuaries. While a few germane references to the literature are made, this document is not intended to be a tutorial on the physics and ecology of estuaries, nor on the range of modeling techniques of potential application. Rather, it attempts to present a succinct summary of methods that are presently sufficiently developed and suitable for application to Texas estuaries, for consideration by the Basin and Bay Expert Science Teams (BBESTs). For detailed background information on estuaries and the coastal environment, the 2004 Science Advisory Committee (formed under Senate Bill 1639) report (SAC, 2004) and citations therein should be consulted. Emphasis here is placed upon delineating the basic approaches of available methods, identifying the necessary supporting data and analyses, and stating their strengths and weaknesses. Section 2 reviews briefly the guidance offered by previous state scientific advisory committees regarding what constitutes a "sound ecological environment" and how that might apply in the bay and estuary context, particularly with regard to flow regimes as noted in Senate Bill 3. Section 3 identifies various sources of available hydrologic, abundance, habitat, salinity and water quality data for Texas bays and estuaries and discusses existing tools that constitute the "State Methodology", and how they have been used for evaluating these data in the context of establishing appropriate

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[1] References are listed in Section 7 of this document.

freshwater inflow needs. Various methods for using the available data to develop freshwater inflow recommendations are described in Section 4, with key decision points involved in selecting and applying the various inflow methodologies briefly highlighted along with each method's strengths and weaknesses. Other considerations, including the role of nutrient and sediment delivery in sustaining the ecological environment of bays and estuaries and the issue of how instream flow recommendations might be integrated with freshwater inflow recommendations in a particular basin, are discussed in Section 5. Finally, SAC observations and recommendations regarding information presented in the document and how freshwater inflow recommendations for the bays and estuaries could be established within the scope and timeframe of Senate Bill 3 are summarized in Section 6. References cited in the text of the document are listed in Section 7, and a list of contributors is presented in Section 8.

# SECTION 2
# STRATEGIES FOR SPECIFYING INFLOW REQUIREMENTS

Senate Bill 3 provides that the BBESTs are to “develop environmental flow analyses and a recommended environmental flow regime for the river basin and bay system for which the team is established through a collaborative process designed to achieve a consensus. In developing the analyses and recommendations, the science team must consider all reasonably available science, without regard to the need for the water for other uses, and the science team’s recommendations must be based solely on the best science available.”

Senate Bill 3 defines “environmental flow analysis” as the “application of a scientifically derived process for predicting the response of an ecosystem to changes in instream flows or freshwater inflows.” “Environmental flow regime” is defined by Senate Bill 3 as “a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent and persistence of key aquatic habitats in and along the affected water bodies.” As applied to bay and estuary inflows, this includes, but is not limited to, addressing issues such as the required frequency of various flow amounts or inflow patterns needed during very dry periods, as well as the frequency of higher flows during wet years that help sustain a healthy bay and estuary ecosystem.

The legislation does not define “sound ecological environment.” However, the recommendations from the SAC (2006) to the Governor’s Environmental Flows Advisory Committee provided the following *guidance*, stating that a sound ecological environment is one that:

- sustains the full complement of native species in perpetuity;
- sustains key habitat features required by these species;
- retains key features of the natural flow regime required by these species to complete their life cycles; and
- sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.

Underlying each of these is the need to establish relationships between elements of the environment, including flows, and the native species and their functions.

## 2.1 THE ESTUARY ECOSYSTEM: COMPONENTS AND INTERACTIONS

Figure 2.1-1 is a highly simplified diagram of the major physico-chemical and biological variables of the estuarine ecosystem, in which the arrows represent causal connections. Despite the simplifications — e.g., suppression of variation in space and time of each of the components, omission of several components, such as temperature, known to exert important controls, compression of several or many variables into a single component, such as nutrients and nonfishery organisms — this diagram demonstrates that the estuarine ecosystem is complex, comprised of many variables and their interactions.

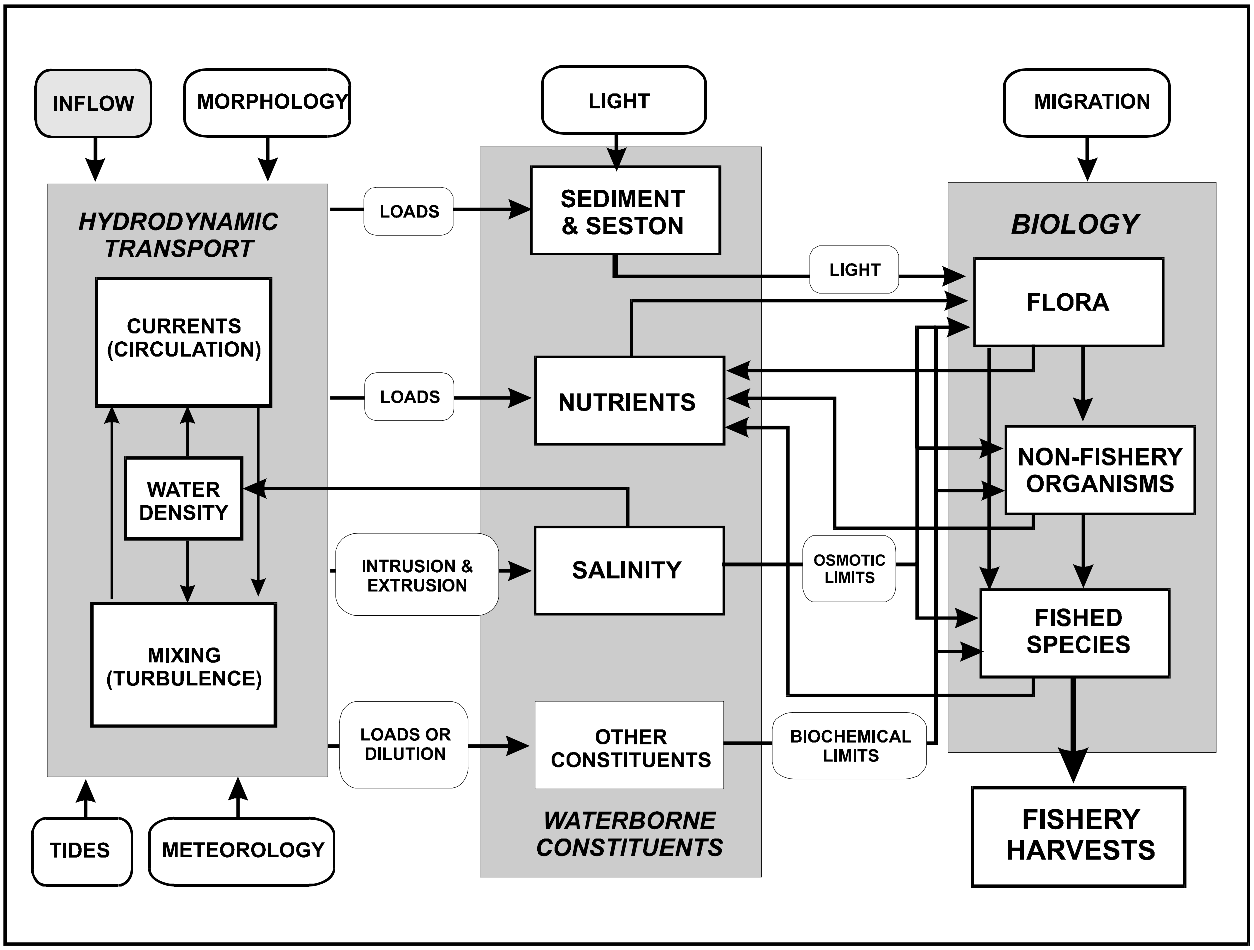

**Figure 2.1-1 - Schematic Diagram of Estuarine Ecosystem**

A few features of this system deserve special mention because they have important ecological function or relevance and because they depend directly on the inflow regime. Much of the complexity of estuaries derives from their nature as a transitional watercourse between freshwater and marine water. This is reflected in the multiple external forces controlling the estuary. The major Texas estuaries are coastal embayments, broad systems with complex morphology that develop internal circulations important in the distribution of waterborne constituents and biological populations. The exchange between estuary and sea is mainly effected by tides, gravity currents and meteorology (especially wind stress). Exchange between estuary and sea also manifests itself in the organisms, as indicated in Figure 2.1-1 by the external control of "migration". Many of the important estuarine animals, notably major fish and shellfish species, migrate between the sea and the estuary at various life-history stages. Most immigrate into the estuary from the sea as young, and mature in the estuary, taking advantage of sheltered, food-rich environments, then return to the sea as adults. Finally, the subdivision of the biological components is on practical concerns rather than the usual compartments of flora (producers), herbivores (first-order consumers), and carnivores (higher-order consumers), because the animals are distinguished according to whether they represent a commercially or recreationally important species. This is an acknowledgment of the concerns of many stakeholders with the economic use of the estuary.

A direct measure of the physical exchange with the sea is the salinity distribution within the estuary. Salinity is the quintessential estuary parameter. It is the concentration by mass of dissolved salts in a water sample. Because the salinity of freshwater is essentially zero, and water in an estuary is a mixture of freshwater and seawater, the value of salinity is an indicator of the proportion of seawater in the mixture and is an excellent natural water tracer, which generally ranges from zero in and near the sources of freshwater inflow into the estuary to a maximum value in the mouth or inlets of the estuary, where it joins the ocean. (See Ward and Montague, 1996, for additional discussion of the function, utility, and modeling of salinity in estuaries.) Marine sea water in the Gulf of Mexico contains about 3.5 % salts (in conventional units 35 parts per thousand, ppt, ‰, practical salinity units, psu, or simply "salinity" without explicit units[2]). The waters of bays and estuaries generally exhibit a gradient in salinity from fresh water at the river mouth to full-strength sea water at the marine end.

The presence, or absence, of salts in water is a mediator in its biological function, as indicated in Figure 2.1-1. Most freshwater organisms cannot survive if salinity is too high, and most seawater organisms cannot survive if salinity is too low. An estuary is therefore an inhospitable environment for these "stenohaline" organisms. There are, however, "euryhaline" organisms that have a physiological capability to function—even thrive—in the intermediate and variable salinities of an estuary. The range and distribution of salinities can therefore be important demarcators of suitable habitat for estuarine species. The spatial estuarine gradient is fundamental for regulating differences in the functions, habitats, and integrity along the salinity gradient. Much is known about salinity gradients in estuaries and the average salinity over long time periods is an indicator of organisms' habitat. Areas where salinity variability is low (i.e., the coefficient of variation is <50%) tend to be more diverse and productive, and areas where salinity is highly variable (i.e., the coefficient of variation is nearly 100%) tend to resemble disturbed systems with lower diversity and many smaller organisms (Montagna and Kalke, 1995; Palmer et al. 2002; Montagna et al. 2008). On the other hand, some species, well-adapted to the high range of salinity in an estuary, tend to be relatively insensitive to its variation.

Inflow plays several roles in the estuary ecosystem, of which for the purposes of environmental flow evaluations, we emphasize three: (1) diluting seawater, thereby reducing the salinity of the mixture of fresh and salt water, and creating a gradient of salinity across the estuary; (2) providing an influx of nutrients derived from the land surface of the estuary's watershed; (3) providing an influx of suspended sediments, derived from the land surface, or eroded from the stream channels. It is through these intermediate effects that inflow exerts an influence on plant

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[2] Salinity is typically measured by conductivity, which is in mV. A mathematical conversion is used to restate measurement in units as 3.5 g salt in 1 kg sea water, which is 35 parts per thousand, ppt, or ‰. A problem arises in that electrical current is converted to a proportion of the unit mass differences of the solid salt in water. This has been termed "practical salinity" by UNESCO (1981) and Millero and Poisson (1981). Today most oceanographers simply refer to "practical salinity" without explicit units (Millero et al. 2008).

and animal organisms in the estuary, i.e. its effect is indirect rather than direct. Moreover, it is not simply the magnitude of inflow that governs these effects, but its frequency, timing and duration are crucial considerations as well, especially the occurrence of higher episodic (pulse) flows and the establishment of sustained low inflows. The higher flow events are mainly responsible for influxes of nutrients and sediments into the estuary, and are effective in quickly replacing the salt water in the estuary with fresh water. It is the opinion of many estuary ecologists that the timing of organism immigration from the sea into the estuary has evolved to take advantage of seasonal inflow variation, and therefore the suitability of nursery habitats in the estuary and the successful growth of these species are dependent upon both the magnitude and timing of seasonal pulses of inflow. Even under drought conditions, inflows also appear to play a crucial role by providing zones of moderated salinities.

The above description of the role of inflows in the estuary, of providing variability upon which many organisms respond favorably, as well as the role of pulse "events" in supplying nutrients and sediment to the watercourse, is a clear parallel to the roles of streamflows in the stream environment (SAC, 2009a). There is, however, a central difference between the roles of flow in the river or stream, and in the estuary. In the riverine setting, flow is the dominating variable that controls almost all of the hydrographic and biological processes. In the estuarine setting, as depicted in Figure 2.1-1, inflow is one of several variables, such as exchanges with the sea driven by tides and winds, internal circulations driven by density differences, wind set-up, and channelization, all of which can influence biology and the interaction between marine and estuarine populations (both flora and fauna). In the estuary, there are multiple stressors and multiple physical drivers. For example, algal blooms, low oxygen events, pollution, thermal stress, physical stress, or combinations of these external variables can effect the biology or even be the dominate factor relative to the effects of inflow. Yet, the role of inflow is significant, and likely the dominant factor influencing estuarine biology in Texas, as evidenced by the change in character of the biota of Texas bays when progressing from the high inflow estuary of Sabine Lake down the coast to the often hyper-saline Laguna Madre.

The diagram of Figure 2.1-1 also serves as a schematic map of the variables and processes that would need to be represented in a *deterministic* model of the estuary. Such a model would be a coupled simultaneous calculation of each of the indicated variables carried out over a computational network that resolves the detailed spatial variation within the estuary and adjacent coastal zone, and employing a time increment to resolve time changes significantly shorter than a day. While such *deterministic* models have been under development for at least half a century, there remain some formulation and major operational difficulties in their application, as well as a requirement for data that are generally nonexistent. In any event, no such comprehensive model encompassing all the known estuarine processes presently exists for any of the Texas estuaries, and will not likely become available within the time frame of the BBESTs. Instead it will be necessary that the BBESTs rely upon sets of measurement from the estuary of concern and accompanying statistical evaluations, perhaps combined with limited deterministic models, to infer responses of the ecosystem to inflows.

Given the limited time available to the BBESTs, it will not be feasible to quantify each of the cause-and-effect relations diagrammed in Figure 2.1-1 by such an approach. Instead, the complexity of Figure 2.1-1 (simplified though it may be relative to reality) needs to be further distilled to represent the most fundamental relations of inflow and ecosystem in a form that may be feasible for determining inflow requirements. This is diagrammed in Figure 2.1-2, and is presented as a "conceptual model" of the causal connection(s) between "biology" and "inflow". The "nutrients" and "suspended solids" components are shown in grey to reflect the present thinking of the SAC to address these as *overlays*, see Section 5. The primary determinants are the relation of salinity to inflow coupled with the relation of biology to salinity, and the direct relation of biology to inflow, though the data requirements and analytical methods will be more demanding to establish such a relation, which is why it is shown as a broken line in Figure 2.1-2. Though Figure 2.1-2 may represent the conceptual model upon which is based an analysis of flow requirements, the complexity of the problem that has been suppressed in order to achieve this illusion of simplicity needs to be borne in mind by comparison to Figure 2.1-1, along with the precept that *any variable or relationship not explicitly considered becomes a source of variance*.

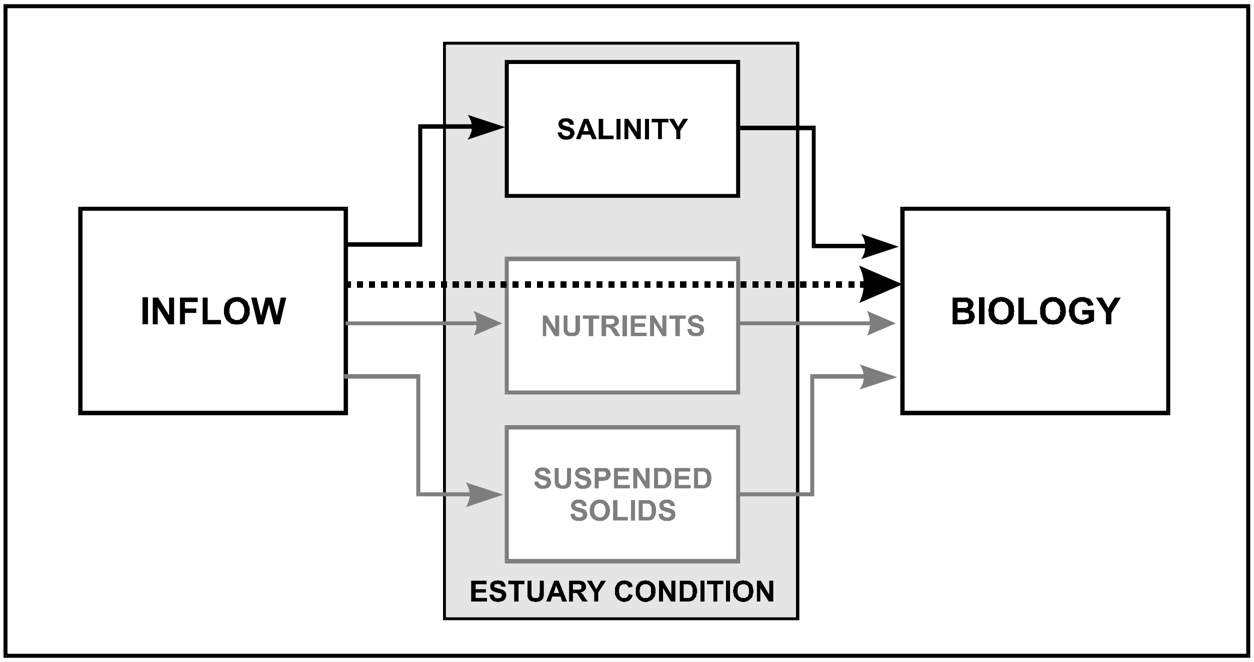

**Figure 2.1-2 – Schematic of Relation of "Biology" to "Inflow" (Compressed from Figure 2.2-1)**

The conceptual model of Figure 2.1-2 is consistent with the general scientific approach to the problem of delineating the effect of inflows on the estuarine ecosystem. Variations of this model can be traced back to Copeland (1966). In recent years, it has appeared in Sklar and Browder (1998, their Figure 1) and Alber (2002, her Figure 1).

Not only does Figure 2.1-2 encapsulate the cause-and-effect connection from inflow to other aspects of the estuarine ecosystem, it also summarizes the historical development of the subject, and depicts the requirement for data and sophistication of analysis. Historically, all freshwater inflow methodologies started from the perspective of hydrology (i.e., flow), later focusing on the distribution of water quality in the estuary, and more recently addressing the organisms in the estuary. This historical development is in part data-driven. Of the many sources of data relevant to the estuary, the most extensive and reliable is that of freshwater inflows. Data on water properties and chemical constituents of water are generally much sparser, and fisheries harvest and fisheries-independent data are sparser yet. The data base for hydrology would support various analyses at a higher level of accuracy and sophistication than could be attained for waterborne constituents such as salinity or nutrients, much less for the biology. But this historical development was also driven by the relative ability of scientists to formulate the underlying cause-and-effect relations, which diminishes with distance to the right in Figure 2.1-2. The problem quickly encountered in the conceptual model of this diagram is that the relationships between biology and hydrology are complex and embedded in the food web and material flow dynamics of estuaries. One cannot grow fish by simply adding water to a fish tank.

In the end, biological resources in estuaries are influenced by the *effects* of inflow, notably on salinity, nutrients and sediments, not inflow *per se*. This is a different situation than that of a river or stream, where the actual velocity associated with river flow is an important ecological determinant. In order to determine these effects in an estuary, an even greater level of accuracy and sophistication is required of the analyses than that for inflows, with a concomitant demand for data. With distance to the right in Figure 2.1-2, the need for data from the estuary increases, but the base of available data diminishes. Also, with distance to the right the need for physical insight and mathematical complexity increases. These facts, early impediments to progress, are still with us and must be addressed by the BBESTs. Typically, the information base for an estuary will support the quantification of one or two of the cause-and-effect linkages of Figure 2.1-2, and usually at a rudimentary level.

## 2.2 HYDROLOGICAL CHARACTERIZATION

"Inflow" is in fact a complex function of time and space. The first step in quantifying the relationship(s) implicit in the conceptual model of Figure 2.1-2 is characterizing this variable, i.e. processing the inflow data to isolate and expose those features considered to be important in determining the ecological response of the estuary to various inflow situations. Essentially this process is a characterization of patterns of inflow, driven by climate, that reoccur fairly regularly and with some degree of predictability. Such a characterization then becomes the basis for constructing a sort of hydroclimatology for the estuary.

In applying inflow data to the analysis of an estuary, the analyst must also specify the period of record over which the analysis is to be performed. Generally, the longer the period of record the better, to ensure representation in the record of the full range of inflow hydroclimatologies. But the analyst must carefully define the purpose of the analysis, and how that purpose may be affected by watershed alterations during the record. For example, in a study of the association between resource data, such as salinity or organism abundance, and inflow, the historical record (for the same period as the resource data record) would be indicated. For estimation of inflows under some planning or management scenario, however, it may be necessary to employ a subset of the record during which some watershed condition was sustained, e.g. use of an early portion of the historic record to estimate pre-development conditions, or selection of a time interval to depict drought, or to employ a modeled or synthesized inflow record such as that used in the

TCEQ's Water Availability Model (WAM), e.g., for a present or projected level of human development in a particular river basin.

In this regard it is also important to be cognizant of the continuing evolution of the bay systems in response to many independent processes. Most of the data and studies available for Texas bays were obtained in the last several decades after and during major changes in the pattern of inflows, sediment and nutrient inputs, the degree of interaction with the Gulf, and fishery harvests. In effect, such data are snapshots of evolving systems—valuable to build understanding. But as time passes and the bays continue a gradual evolution, such data will need to be renewed.

A prominent feature of inflow into an estuary is its extreme variability in time. It is tempting to average out this variation to expose larger-scale temporal signals of inflow, which then may have explanatory value in interpreting historical water quality or ecology of the estuary. An implicit example of this was given above, where was noted the change in character of the estuaries along the Texas coast from Sabine Lake to Laguna Madre, and interpreted as a response to the decrease in long-term mean inflow from east to west (see also Orlando et al. 1991). Another example is the employment of annual flows in explaining year-to-year variation in water quality, production, or species abundance, but this is generally more successful in watercourses like lakes and large rivers than in estuaries.

The variation within the year, notably the occurrence of pulses of flow and of sustained, usually low flows over a substantial period, is thought by many ecologists to be a prime control on the ecological health of the water body. Moreover, though the annual flows may vary from year to year, there is often a general consistency in the relative seasonal variation within the year. The problem is how to best characterize this variation to identify those features of potential ecological importance. There are two broad time-depiction strategies summarized in the following sections: the cyclical strategy, which seeks an essentially repeatable pattern of flow variation from year to year, and an inflow "event" strategy in which various time signals are defined and the inflow time series analyzed for their occurrence. This dichotomy of strategy obtains in any watercourse, but it is a source of peculiar difficulty in an estuary because (1) the transit of streamflows through the watershed to their mouths in the estuary acts as an integrator of the signal, so that the storm pulses and interstorm low flows are "smeared" out; (2) multiple sources of inflow with varying watershed sizes, ranging from peripheral coastal drainages to major basins, with different hydroclimatologies, create a complex time signal; (3) these multiple inflow sources can obfuscate the role of specific inflow sources on critical habitat regions; (4) these multiple inflow sources may exhibit different water quality, thereby obfuscating the roles of inflow as nutrient and sediment suppliers; (5) the multiplicity of organisms in the estuary ecosystem, from freshwater to marine, and both temporary and permanent residents, entails potentially different responses to the inflow time signal.

### 2.2.1 Cyclical Analysis

Because the intra-annual variation in streamflow is keyed to precipitation on the watershed, which in turn is driven by seasonal atmospheric circulation patterns, it is frequently hypothesized that there is a predictable seasonal "pattern" of inflows characteristic of the hydroclimatology of the watershed, which further exerts a control on the organisms whose success is “tuned” to this pattern. Such patterns are manifest in Texas hydroclimatology, evidenced most clearly by the season(s) of maximum precipitation (e.g., Ward, 2005). This is the genesis of the analysis of inflow for an annual cycle (i.e., tracking the annual revolution of the earth about the sun). The role of a “cycle” in temporal fluctuation was identified by Colwell (1974) as supporting “predictability” in an ecosystem, and this was analyzed in rainfall and streamflow time series by Gan et al. (1991), who evaluated the effects of binning on the Colwell indexes. In practice, this has become a “calendar period” strategy based upon a hypothetical variation of averages over some convenient subdivision of the year.

Probably the simplest calendar-period approach that attempts to characterize the annual pattern of inflow is to determine statistics of the flows after being subdivided by months, of which the most basic statistic is the monthly mean flow. A plotting of the monthly-mean inflows to the Texas bays certainly suggests a pattern, with winter inflow maximum in the extreme east of the state, shifting to a spring maximum and the appearance of a separate fall maximum further west, see Figure 2.2-1. (This figure plots the relative seasonal variation as a ratio to the period-of-record mean, with error bars indicated the coefficient of variation. What this figure does not show is a decline in mean inflow from Sabine Lake to Corpus Christi Bay of nearly two orders of magnitude. The standard deviation also declines down the coast, but not as much as the mean flow, hence the increase in coefficient of variation.)

The essential hypothesis of the cyclical or calendar-period analysis is that the flows averaged (or accumulated) over a subdivision of the calendar represent a physically meaningful quantity by dint of that calendar period. For example, the March-May period might be asserted to represent runoff due to spring frontal systems. Therefore, the array of March-May aggregated flows exactly quantifies year-to-year variation in this element of the hydroclimatology. Further, this aggregated flow can be identified as an independent variable in response analyses, because that period represents a well-defined component of the annual hydrograph cycle to which other variables, such as water quality or abundance of an organism, respond. The size of the period relative to the time scales of variation in flow determines whether the aggregation in time is merely a computational convenience, to reduce the size of a data file while maintaining the attributes essential to depicting flow variation, or attaches a separate physical significance to the flows over that calendar period. A prime example of the latter is the annual flow computed over the period of a water year, defined (hypothetically) so as to begin in the driest month of the year, thereby capturing the full range of hydrological activity for the annual period.

### 2.2.2 Event-Based Analysis

Two major branches of hydrology address storm hydrographs and periods of drought, respectively. Both of these types of temporal behavior of streamflows are considered “events,” by which is meant a sequence of flows that exhibit some sort of coherent, autonomous behavior in time. The event-based approach seeks to identify these in the hydrological record, usually by mathematical specification, and subject them to analysis as identifiable occurrences, typically determining their statistics of magnitude, probability, and time trends. Their occurrence in the hydrological record is generally approached without regard to calendar, but once identified, these events may be analyzed for seasonal clustering.

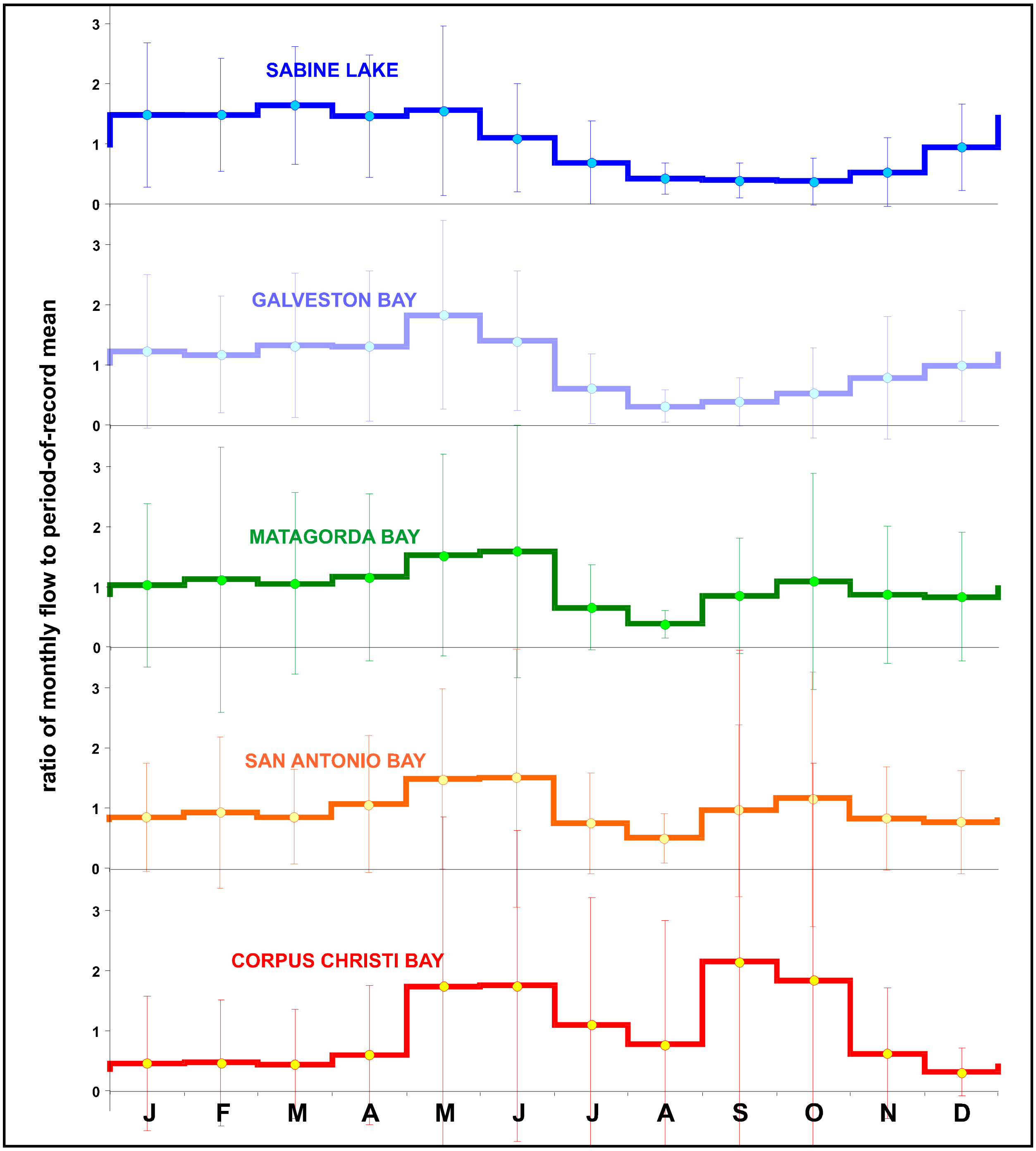

**Figure 2.2-1 – Annual Patterns of Monthly Gauged Inflows into Texas Bays As Averages Over 1941-2000 Period With Error Bars for Coefficients of Variation**
(based on TWDB data)

Examples of hydrological events are shown in the time trace of 1964 flows in the Trinity River at Romayor, Figure 2.2-2. One advantage that storm hydrograph identification enjoys in Texas derives from the fact that precipitation in the state is almost entirely due to deep convection, so rainfall tends to occur in relatively short, intense bursts, which produces a well-defined rise and recession in runoff (see SAC, 2004). These hydrographs are clearly evidenced in the time plot of daily streamflow, e.g. Figure 2.2-2, even though a mathematical algorithm to identify these in the streamflow time series may prove problematic. Another event identified in Figure 2.2-2 is the summer low flow, sometimes referred to as the "summer drought", which is a regular occurrence in many, but not all, years.

Methods for identifying storm hydrographs in the daily flow time series are well-documented and will not be reviewed here. Convenient summaries may be found in Gray (1970) and Pilgrim and Cordery (1993), among others. The initiation of a storm hydrograph is typically abrupt, and algorithms for detecting these events are straightforward and generally successful, challenged mainly when confronted with a complex hydrograph in which multiple storm events are superposed. The termination of a flood hydrograph is more ambiguous, however, because the recession limb tends to be extended and confused by the discharge of water stored in the stream bank and adjacent soil layers (interflow).

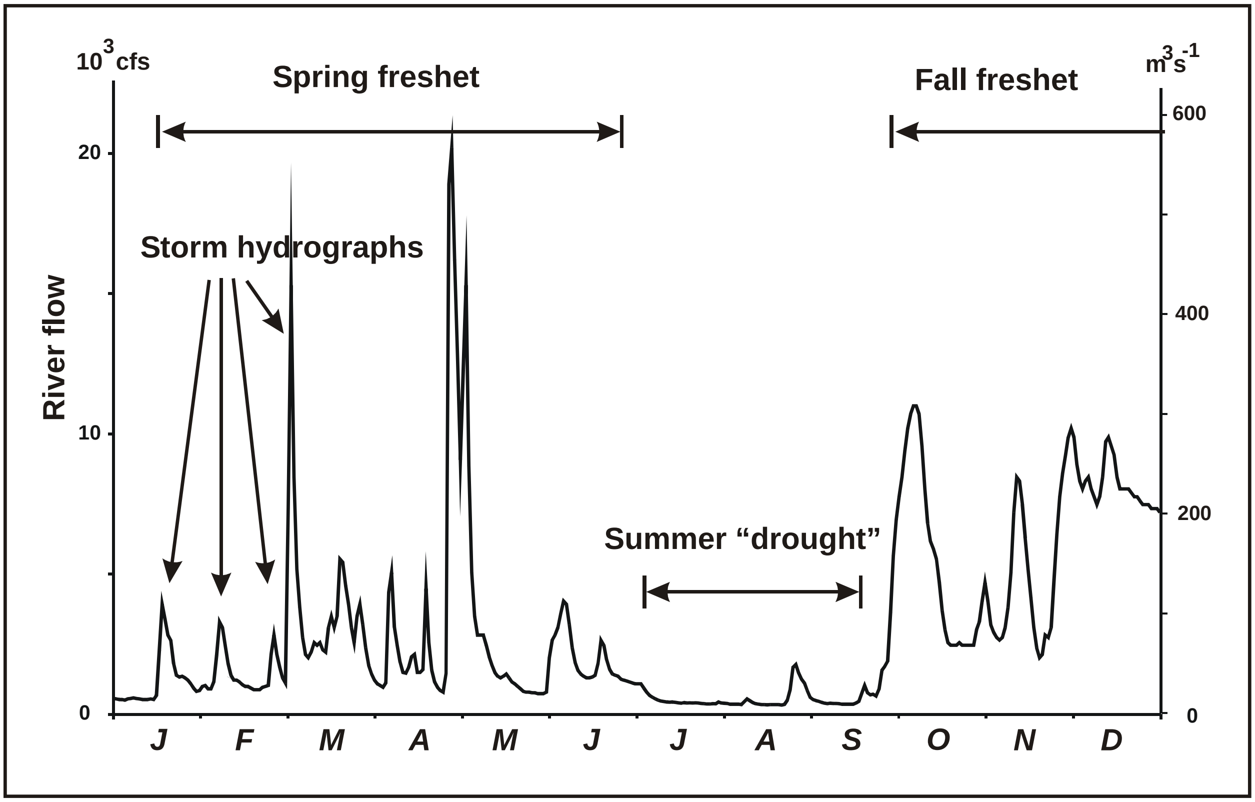

**Figure 2.2-2 - 1964 Daily Flows in Trinity River at Romayor Showing Various Hydrological "Events"**

Another type of event that has received study in recent years is the "freshet" concept. This is a large-scale influx of river flow, generally made up of a series of storm pulses closely spaced within a relatively short period of time (a few months, say). Examples are identified in Figure 2.2-2. The hypothesis underlying the definition of this event is that the estuary is not sensitive to the details of time fluctuation during the period of freshet delivery, because the responses of the salinity structure and biota act as a time integrator. The key parameters of a freshet are its volume, date of onset, and duration, and any of these may vary from year to year. Although these freshets can occur any time during a year, they tend to favor certain seasons in which meteorological activity is concentrated, and therefore they are the primary determinants of seasonality of river flow.

Freshets were used in the Water Quality Status and Trends projects of the National Estuary Programs (NEP) for Galveston Bay and Corpus Christi Bay to characterize hydrology. The analysis was based upon monthly inflow data, in which a freshet was defined to be the three-month period of maximum inflow for a given year or half-year. The pre-specified freshet length simplifies the analysis, and the use of monthly data reduces the file sizes to a more convenient length. (Use of monthly data would also make the NEP method potentially useable with the Water Availability Model (WAM) results.) More recent work has generalized this so that daily (rather than monthly) streamflow data are used in delineating freshet events, which is performed by a mathematical process. An example of the results of a freshet analysis, for the Colorado River, is shown in Figure 2.2-3 (see MBHE, 2006). The $y$-axis marks time, increasing upward but folded back to the $x$-axis at the beginning of each year, plotted along the $x$-axis. Freshets are shown as rectangles whose lower boundary corresponds to the beginning of the event, upper boundary corresponds to the end, and whose area is proportional to the volume of the event. Thus, the tendency for freshets to occur in a given season can be inferred by eye. As a standard of comparison and a unit of measure, the area of the red square represents the volume of Matagorda Bay.

The freshet analysis may prove a better characterization of inflows for purposes of assessing the response of biology. Preliminary statistical analyses in Matagorda Bay (MBHE, 2006) using seasonal freshets as an independent variable yield greater explanatory power for the variation of annual-mean abundance for several major species than can be achieved using calendar-period flows.

## 2.3 ESTUARY CONDITION AND HABITAT CHARACTERIZATION

By "estuary condition" is meant the suite of physical and chemical variables potentially important, either directly or indirectly, to the functioning of the estuary ecosystem. Among the physical variables are included tides and tidal currents, wind-driven circulations, surface waves, water temperature, light within key spectral bands, and suspended solids in the water column. Among the chemical variables are included salinity, species of inorganic nitrogen and phosphorus, dissolved oxygen, silicates, various organic compounds, and both inorganic and organic toxins. Habitat refers to the complex of physical and chemical conditions necessary to support an organism or community of organisms. More broadly, it includes other organisms that may act as prey or predator, provide substrate (e.g., reefs or marshes), or process nutrients and organics into assimilable forms. The network of relations diagrammed in Figure 2.1-1 implicitly

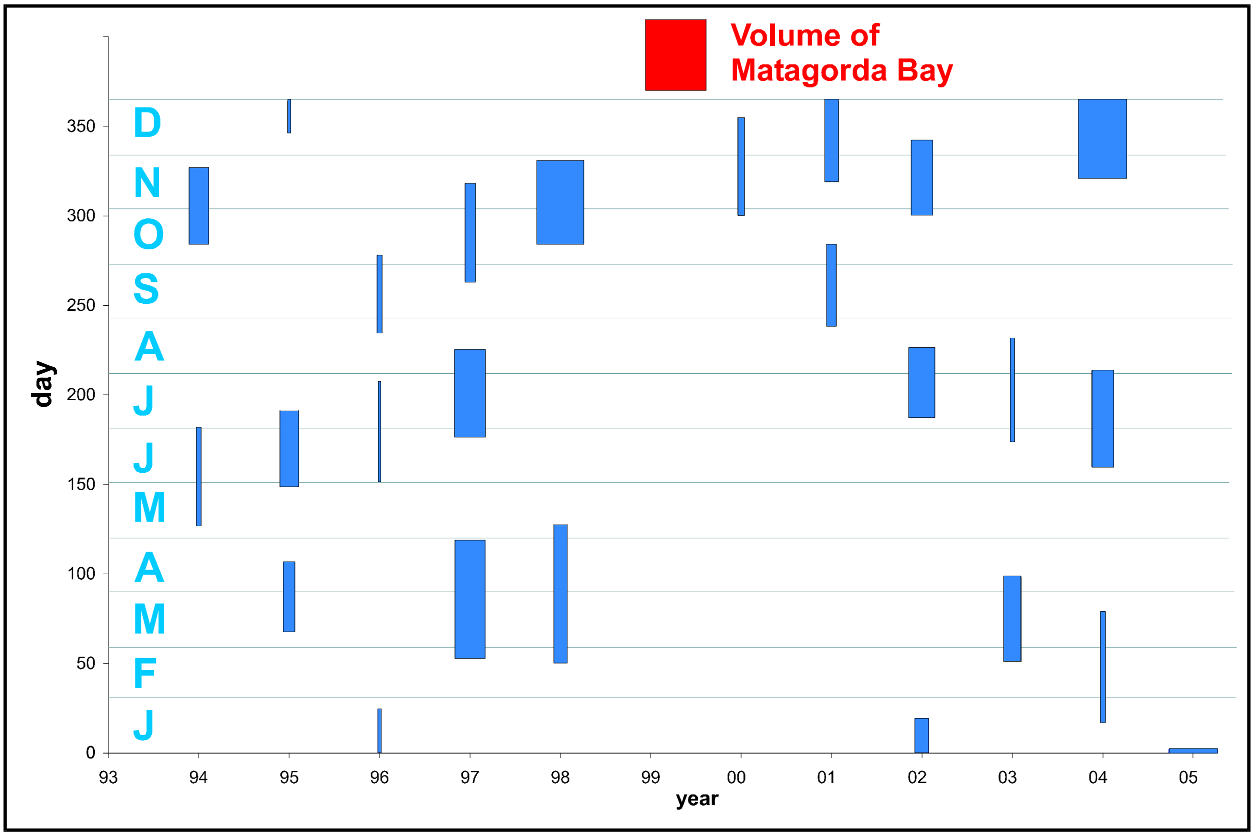

**Figure 2.2-3 Occurrence of Freshets in Colorado River 1993-2005**

includes habitats. Habitat characterization consists foremost in selecting, among the myriad variables and relations comprising habitat, which habitat variable(s) will be explicitly considered. Clearly, estuary condition is an important aspect of habitat. In the stripped-down relationships of Figure 2.1-2, only three parameters of estuary condition are shown, and the only habitat variable remaining is the salinity zone (although the nutrient/sediment overlays may be relevant to some habitats, and some specific organisms may be included in the biology component that provide a habitat function).

The relation of salinity at a region of an estuary to inflow is a complex dynamic response. While salinity is affected by inflow, there are complications because of the interactions between tides and geomorphology. In addition, the intrusion of salinity from the sea into an estuary is governed by several processes, notably gravity currents, tides and mixing (see Figure 2.1-1), none of which is directly affected by inflow. In a simple statistical relation of salinity on inflow, even when inflow is characterized properly, the relations are noisy, because these other processes affecting the time variation of salinity are neglected in such an analysis and therefore increase the variance about the relation.

An example is shown in Figure 2.3-1 showing the relation between point measurements of salinity in a region of Galveston Bay (combined over a number of data collection programs) and inflow, where the scatter is considerable (standard error about 5 ppt) despite the proximity of the data region to the source of inflow. Nor is this scatter a consequence of the (typically) sparse point measurements in this data set. Figure 2.3-2 displays the daily mean salinity measurements from the TWDB Trinity Bay sonde, whose regression is almost identical (with a standard error of about 4 ppt). This scatter in fact underlies all of the relationships sketched in Figure 2.1-2, and entails considerable uncertainty about the salinity (or nutrients, or sediment) predicted from a level of inflow (which is further compounded if the inflow characterization is errant).

However, this is not to suggest that relating salinity to inflow is subject to so much variance that no inference can be made. Because of the pivotal role that salinity will likely play in the work of the BBESTs, alternative formulations of the independent inflow variable, separated geographically or temporally, should be explored.

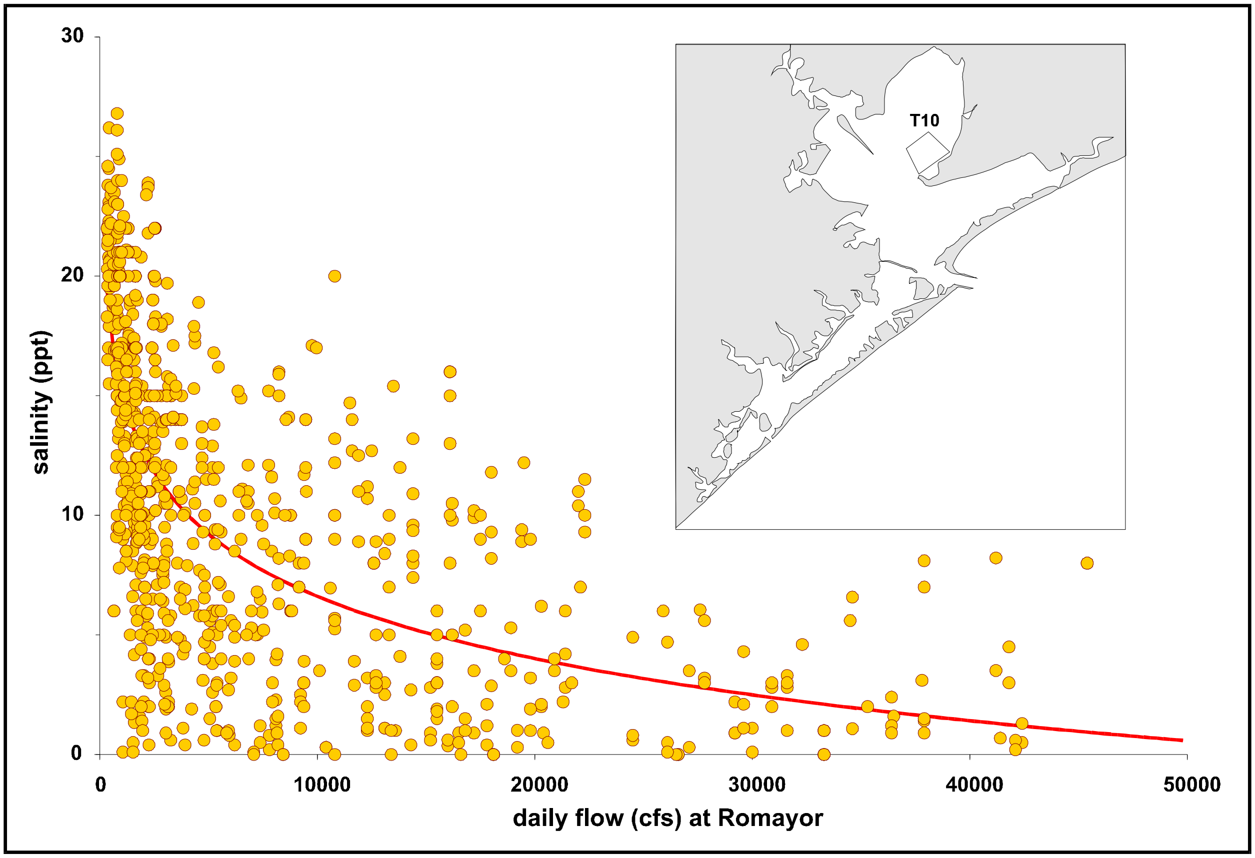

**Figure 2.3-1 Surface Salinity in Segment T10 Versus Trinity River Flow at Romayor with 30-Day Lag of Salinity Behind Flow for 1958-1991**
(from database compiled by Galveston Bay National Estuary Program)

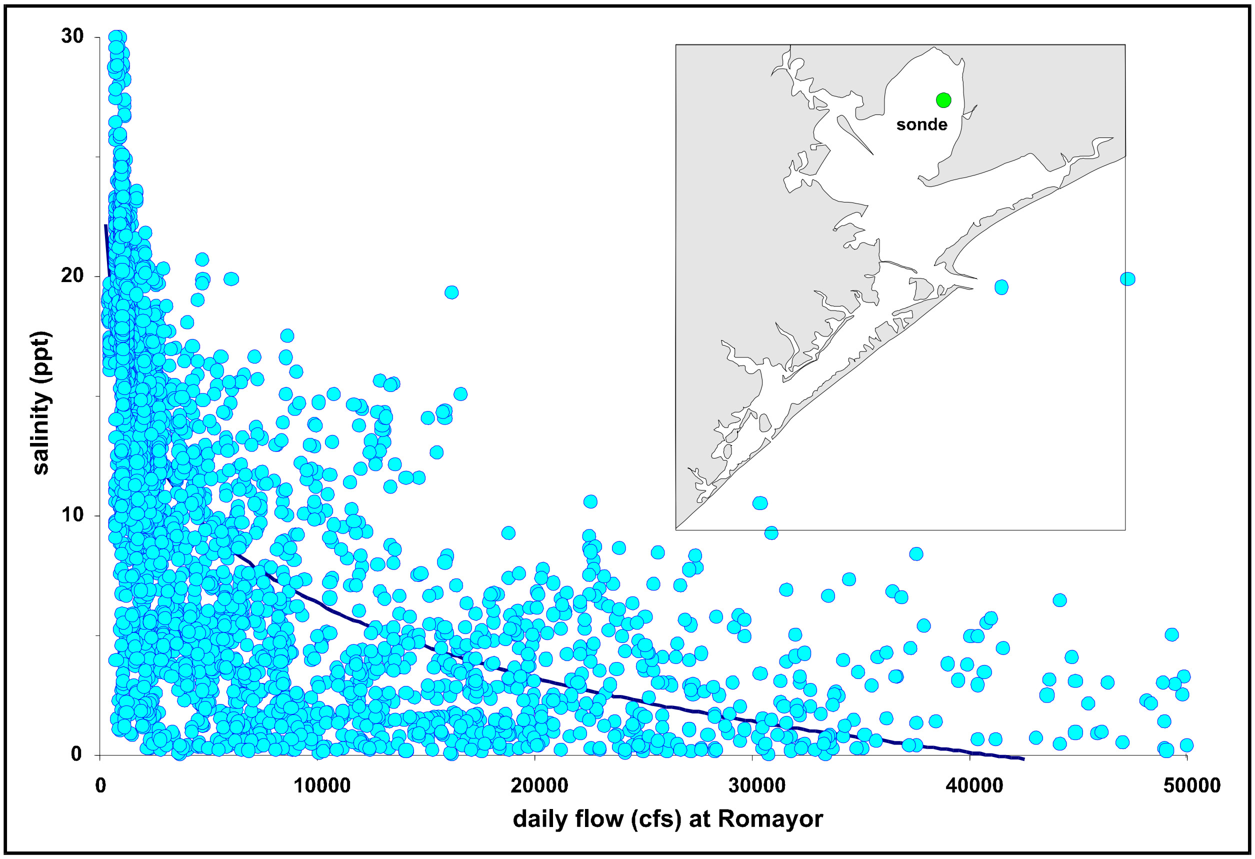

**Figure 2.3-2 Surface Daily-Mean Salinity at Trinity Bay Sonde Versus Trinity River Flow at Romayor with 30-Day Lag of Salinity Behind Flow for 1986-2007**
(from data files of Texas Water Development Board)

The definition of habitat includes the notion of a distribution in space, which might be a value of area (or volume), an overlay of geomorphic region with biochemical properties (the nearshore environment being a prominent example), or a specific region of an estuary historically associated with a complex of biochemical properties (e.g., a prominent oyster reef). In order to quantify this aspect of habitat, the characterization may include any of these spatial attributes. In particular, the salinity-zone specification attaches a measure of the spatial area (or volume) included within a range of salinity values that is not tied to a specific region of the estuary. Examples of this approach to habitat characterization are given in Section 4.2.

## 2.4 BIOLOGICAL CHARACTERIZATION

Biological characterization consists of selection of which biological components are to be addressed and what spatial and temporal formulas are to be used in quantifying the data. The biological components can be individual species or can be complexes of species, perhaps parameterized by some ecological structural measure such as diversity. These possibilities are discussed further below. The strategy of Figure 2.1-2 requires that, once the biological components are identified, either the habitat requirements are delineated, which may be confined to salinity, or that a direct relationship on inflow be developed.

### 2.4.1 Key Species Approach

The key species approach to characterizing the biology of a watercourse for purposes of impact assessment has been employed for at least half a century. It entails the focus on one or several so-called key species. Basis for selection of a key species is either (1) that the species enjoys some prominence, typically as a favored recreational target, as a commercial fishery hence having economic significance, or as a charismatic species commanding widespread public interest, or (2) that the species typifies in some way a key element of the ecosystem. (In contrast, a "keystone" species is one that has an impact on the structuring of a community that is disproportionate to its population size, Paine, 1966.) In Texas, shrimp and crab are examples of key species supporting important commercial fisheries, and black drum, flounder, red fish, and seatrout are examples of species favored by recreational fishers. The whooping crane is an example of an endangered species, which is also iconic to bird watchers. Oysters, seagrasses, and cordgrass (*Spartina* sp.) are examples of individual species that ecologists consider to be representative of important ecosystem engineers, or foundation species, that create habitats and provide important functions that sustain ecosystem services. The utility of key species is enhanced if they exhibit sensitivity to inflow-controlled parameters such as salinity or nutrient concentrations.

The oyster is an unusual candidate in that (1) it supports a major commercial fishery, (2) it is an important element of the ecosystem, providing a substrate for an entire, unique community, and (3) because it is a sessile filter feeder, it can function as a sentinel, (4) it is considered to be responsive to inflows.

The limiting factor in the application of the key species approach is basic data on the species. Ideal data would result from a monitoring program in the estuary maintained over many years, and employing uniform sampling gear and protocols. From such a program, the abundance, by life stage, of the species can be estimated over time, and this data used to assess the response of that species to inflows. Typical data sources of this type are academic research programs and agency monitoring projects. The Coastal Fisheries Division Resource Monitoring Program of the Texas Parks and Wildlife Department (TPWD) is an example and a a valuable resource to the state. Since the 1950's, TPWD has monitored the abundance of higher organisms in the bays of Texas, and since the mid-1970's the results of the program have been archived in digital format. TPWD biologists perform regular collections using a variety of standard gear types on nearly a daily basis, and count and report everything caught. The value of this program for monitoring and analysis of the ecosystems of the Texas bays cannot be overstated.

The principal application of abundance data for a key species is to determine whether there is an apparent association of the abundance of that species with inflow, as represented by the broken arrow of Figure 2.1-2. An example is shown in Figure 2.4-1, of white shrimp abundance in Matagorda Bay as a linear function of the volume of the fall freshet (see Section 2.2.2, above). Although, the TPWD data files in their original forms are enormous and not easily manipulated for analysis, several tools have recently been developed by TWDB, TPWD, and the Houston Advanced Research Center to facilitate use of these data (see Section 3.3). However, unless work is already underway (or has been undertaken by others) to apply this data resource in a bay system, it is unlikely that a BBEST will have the time or resources to explore relations of abundance of a key species to inflow. If information does exist on the habitat requirements of that species, then the analysis can be carried out as indicated in Figure 2.1-2, except that the direct relation of species abundance to inflow cannot be addressed.

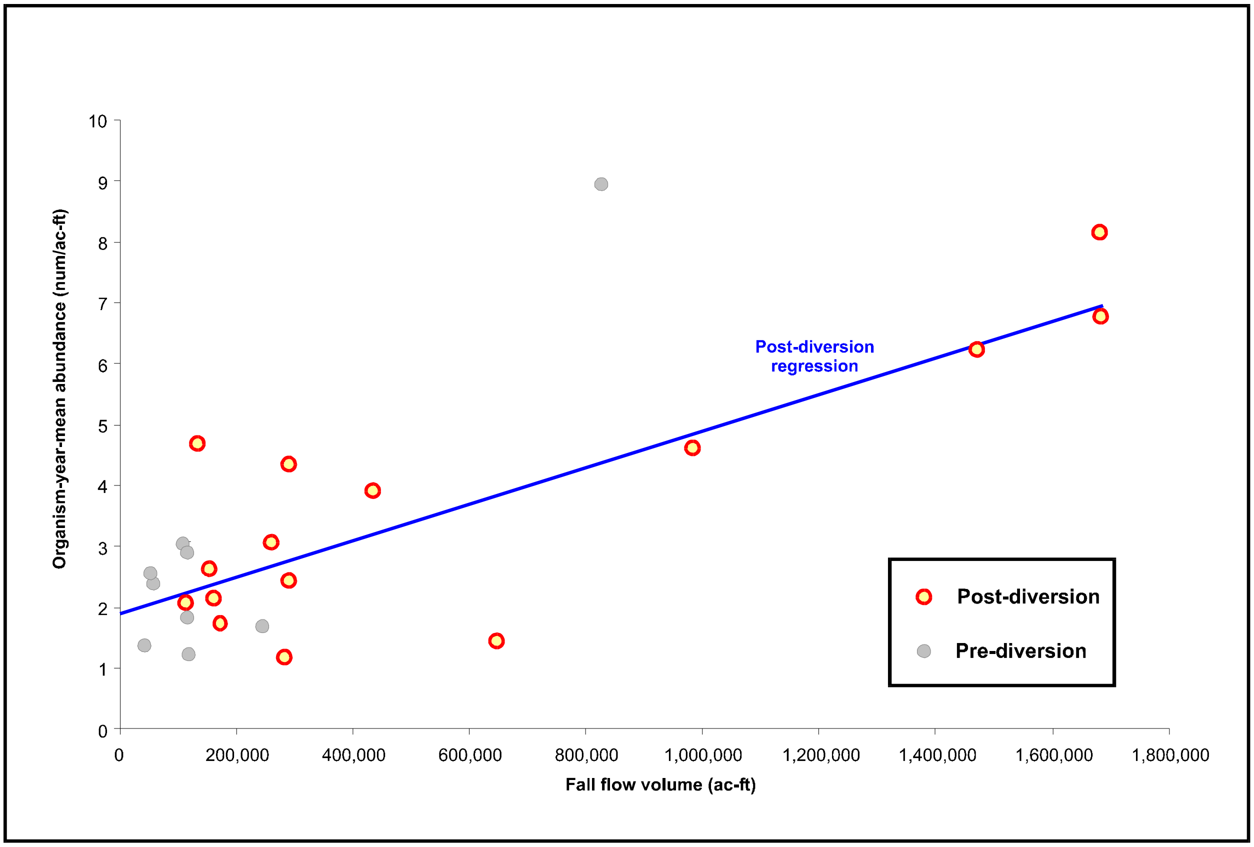

**Figure 2.4-1 – Abundance of White Shrimp in Matagorda Bay Versus Freshet Volume in Colorado River**
**(Diversion refers to the USCE Diversion Project of the Colorado River channel)**

A slight modification of this approach is to substitute salinity for flow volumes to determine the realized salinity range of a species. This approach was developed for Texas (Montagna et al. 2002) but more recently used for the central western coast of Florida (Montagna et al. 2008). The approach is based on a non-linear model, which assumes there is an preferred range for salinity and values decline prior to and after meeting this maximum value. That is, the relationship resembles a bell-shaped curve. The shape of this curve can be predicted with a three-parameter, log normal model:

$$Y = a \times \exp( -0.5 \times (\ln(X / c) / b)2)$$

The model is used to characterize the nonlinear relationship between a biological characteristic (Y, e.g., abundance or diversity) and salinity (X). The three parameters characterize different attributes of the curve, where a is the peak abundance value, b is the skewness or rate of change of the response as a function of salinity, and c the location of the peak response value on the salinity axis (Montagna et al. 2002a). For example, it was determined that the small clam *Rangia cuneata* in the tidal river estuaries of southwest Florida has a salinity range between 1 and 10 psu, with a realized preferred range of 4 psu (Figure 2.4-2).

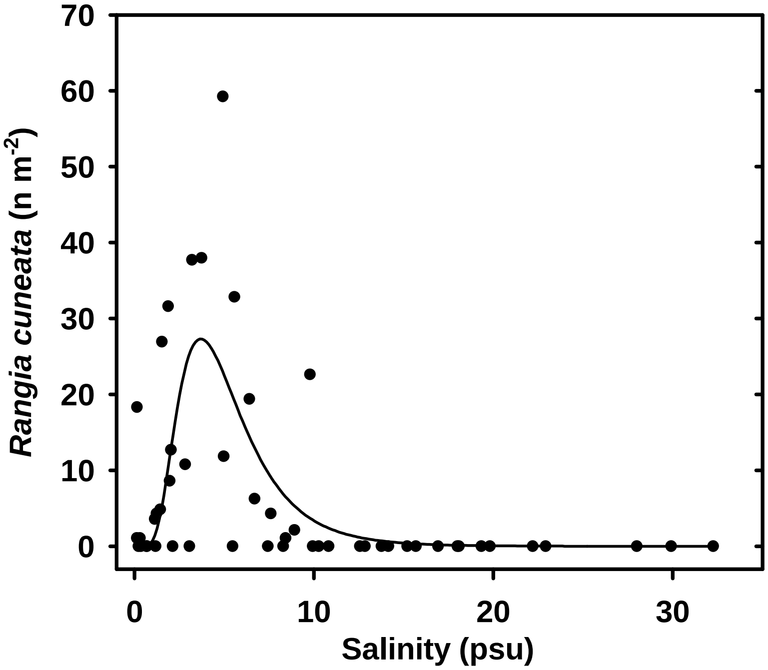

**Figure 2.4-2 – Relationship Between Salinity and Species Abundance in Southwest Florida Estuaries**
Adapted from Montagna et al. 2008

### 2.4.2 Ecological Component Approach

In contrast to the key-species approach, which focuses on single species and their dependency upon habitat and/or inflow, the ecological-component approach identifies a community of species for analysis as an entity. This approach derives from interpreting a "sound ecological environment" in Senate Bill 3 in terms of ecosystem integrity and sustainability. Integrity is the state of the community structure and is acceptable when biological diversity and species composition are comparable to some standard, typically that of natural habitats in the same region. The community is recognized as an important functional unit of the system, or as one that is sensitive to the external factor under evaluation, in this case inflow. This type of community specification may also be important in refining the requirements of nutrients and sediments delivered by inflow.

An example of the ecological-component approach is the use of benthos data in Matagorda Bay to develop a model for the benthic macrofauna component (Kinsey and Montagna, 2005; Montagna et al., 2006; see also MBHE, 2008). Benthic macrofauna are good indicators of environmental condition because they are relatively long-lived, sessile, live in the bay sediments, and respond to food from above; thus, they integrate effects caused by changes in the overlying water over long time periods. The benthic macrofaunal community structure was studied from 1988 through 2007 in two geographic regions of Matagorda Bay, *viz*. Lavaca Bay and the Eastern Arm of Matagorda Bay. Six stations were sampled along freshwater inflow gradients emanating from the Lavaca and Colorado Rivers. The analysis of long-term benthic community structure data revealed strong year-to-year variability in benthic biomass and freshwater inflow, and indicated a general decline in long-term biomass. More importantly, these data also show strong spatial gradients of benthic biomass, productivity, community structure, and diversity related to three identifiable salinity zones within the estuary (Figure 2.4-3).

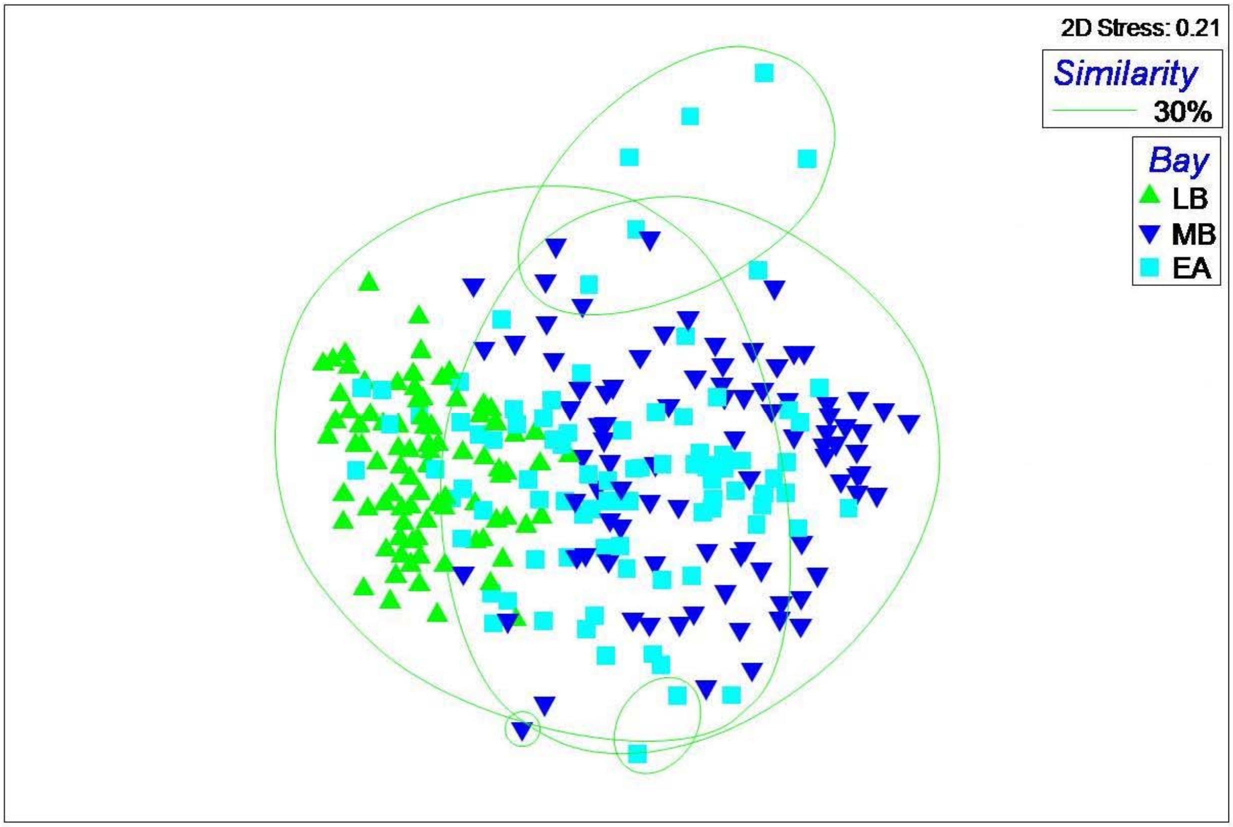

**Figure 2.4-3 – Salinity Habitat Zones in the Lavaca-Colorado Estuary Defined by Benthic Community Structure Using Non-Metric Multi-Dimensional Scaling (LB=Lavaca Bay, MB=Matagorda Bay, EA=Eastern Arm)**
See Clarke and Gorley (2001); Adapted from MBHE (2008)

Using an ecological component approach is simple if there is sufficient data at the species level over the scale of the estuaries and over long periods of time. Much of this kind of data exists for nearly all bays in Texas, but benthic data resides mostly in academic units. In contrast, the TPWD data is publicly available at the species level. If the benthic data can be identified, this approach will be very useful to the BBESTs.

Using the component approach also requires information about salinity in order to use the information to determine inflow requirements to protect ecological health. For example, consider Table 2.4-1, and note that the average salinity in each zone (LB < EA < MB) correlates to the dispersion of the samples from left to right in Figure 2.4-3. Thus, if the average inflow in Lavaca Bay (LB) is reduced so that its average salinity resembles the average salinity in the Eastern Arm of Matagorda Bay (EA), then the dispersion among the ecological components would disappear and the ecosystem would be reduced to just two zones. Should this occur, then the unique Lavaca Bay (LB) community depicted in Figure 2.4-3 would disappear and become similar to the Eastern Arm (EA) community. The loss of diversity of habitat zones could be considered a degradation of the ecological environment.

**Table 2.4-1 Long-Term Average Salinity and Mean Psu ± 1 Standard Deviation for Benthic Samples in Figure 2.4-3**

**Adapted from MBHE 2008**

| Bay | Salinity (ppt) | ± 1 Std. Dev. |
|---|---|---|
| LB | 14.0 | 9.2 |
| MB | 24.3 | 7.9 |
| EA | 21.3 | 8.4 |

### 2.4.3 Ecological Function Approach

An alternative method of biological characterization is to identify key functions, e.g., production, trophic links, reproduction, etc, along with acceptable ranges of indicators of ecosystem function necessary to ensure sustainability. Like the ecological component approach, the functional approach derives from interpreting a "sound ecological environment" in Senate Bill 3 in terms of ecosystem integrity and sustainability. In this case, integrity is the state of the ecosystem processes and is acceptable when structural redundancy and functional processes are comparable to some standard, typically that of natural habitats in the same region. Sustainability is acceptable when an ecosystem maintains a desired state of ecological balance (e.g., the ecosystem provision of ecosystem services from habitats). Typically inflow studies focus on benthos, epibenthos, or nekton community structure and diversity (as indicators of integrity); and oyster reef, seagrass, or marsh plant vegetation cover (as indicators of sustainability).

The functional approach was also used in concert with the component approach in the Matagorda Bay Health benthic studies (MBHE 2008). In addition to time series analysis of the benthic data, a bio-energetic model of macrobenthic biomass was developed to relate biomass to salinity in the two geographic regions (Figure 2.4-4). The model simulates biomass of two macrobenthic groups—suspension feeders and deposit feeders. The former include bivalves and other organisms that filter phytoplankton or graze on benthic diatoms, and the latter include burrowing worms and other organisms that consume organic matter that has settled into the sediment. The model represents the biomass of each benthic group over time as a balance between growth and limitation by the environment and predators. The model was used to calculate the sensitivity of the benthic community to changes in salinity. In general, the model predicts that higher salinity will produce large increases in deposit feeder biomass in Matagorda Bay, but no change in Lavaca Bay, and substantial decreases in suspension feeder biomass in both bays (Figure 2.4-4). Thus, reduced freshwater inflow changes the functional diversity and productivity of both bays.

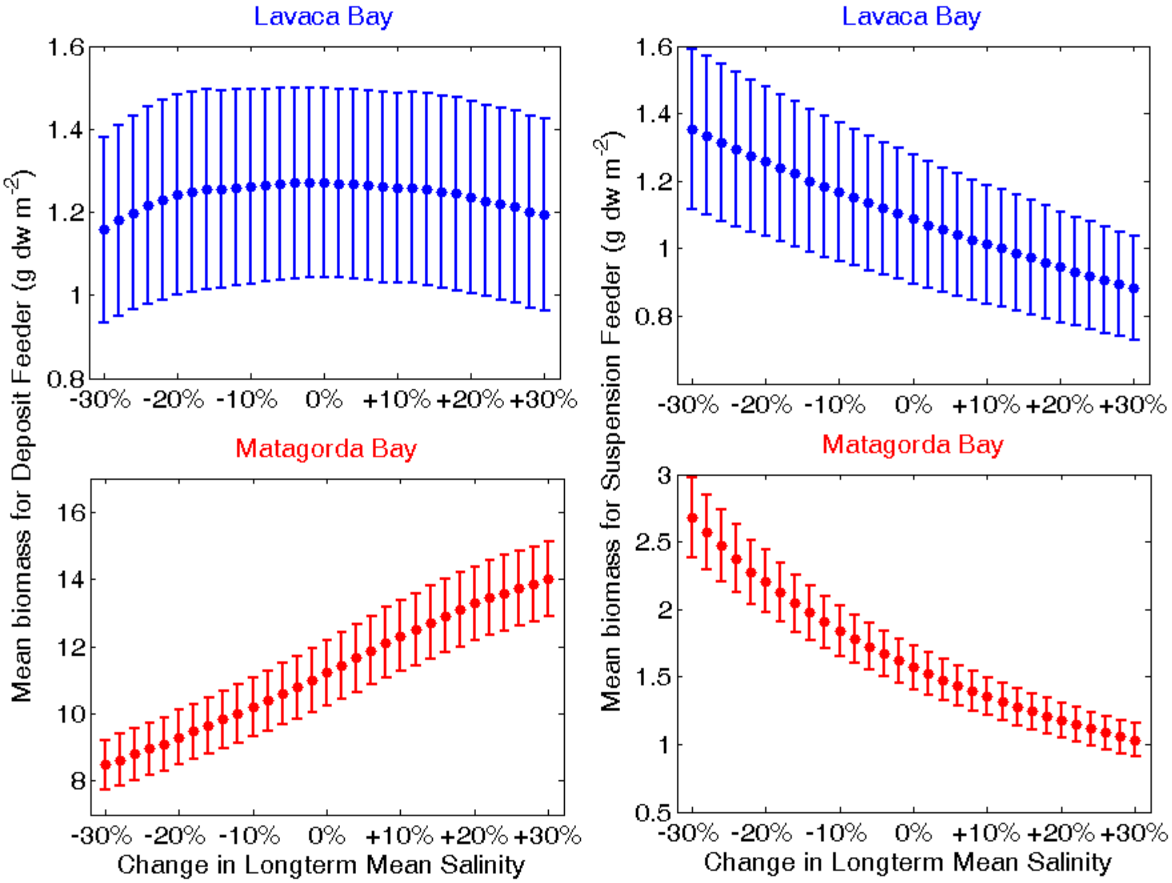

**Figure 2.4-4 – Predicted Change in Productivity of Two Trophic Groups Resulting from Change in Long-Term Average Salinity**
Source MBHE (2008)

Clearly, the viability of this approach to the BBESTs will require access to a considerable base of scientific study of the estuary ecosystem. When such work has been carried out and is available, it will be advantageous for the BBESTs to exploit it. Otherwise, this approach will not be practical within the limited time presently available to the BBESTs. While this approach is likely not practical for the BBESTs to complete within the time frames available, a report on three additional Texas estuaries (Guadalupe, Nueces, and Laguna Madre) will be available in 2010 (Kim and Montagna, 2010).

## 2.5 SUMMARY

The simplified functional diagram of inflow giving rise to estuary conditions that then affect biological components (Figure 2.1-2) affords an approach to inflow determination for an estuary that exploits the existing scientific information base and is at least potentially responsive to the guidance from the August 2006 SAC presented at the beginning of this chapter. Mathematical relationships would be formulated that describe the response of salinity habitat zones to inflow, and the species selected would dictate both necessary habitat properties and the direct relationship, if any, of that species' abundance upon inflow.

The diagram of Figure 2.1-2 is a suggested conceptual model of how changes in inflow will influence habitat, thence biology, in which the arrows depict causal connections. With these relationships quantified from data, the conceptual model would indicate how the effects of a change in inflow would manifest themselves in changes in the selected components of biology. Inflow specification requires two additional procedures by the BBESTs:

1. Formulation of specific ecosystem management goals, e.g. the desired presence/ absence and range of abundance of the key species, and/or the desired range of attributes of the estuary condition, notably salinity
2. Quantification of the range of inflows that correspond to the conditions desired in (1)

There may be a need to conform the format and articulation of the goals to the extent to which the causal relationships from inflows to habitat parameters to key-species abundance, depicted in Figure 2.1-1, can be reliably and quantitatively established for the estuary. At minimum, some insight into the possible effects of inflow can be gained from an analysis of the inflow record itself, together with conceptual interpretations of how the ecosystem responds to inflow. This should be viewed as the default option of Figure 2.1-2, to be elected only when there is no information on the other elements of the estuarine ecosystem.

This situation is analogous to that of the stream or river condition addressed in SAC (2009a). The Hydrology-based Environmental Flow Regime (HEFR) approach is proposed, in which a "regime" of flow is established as a statistical occurrence by month for several categories of streamflow considered to have ecosystem or hydraulic functions, as specified in the Texas Instream Flow Program (TIFP) (TCEQ, 2008)). An analogous approach to the estuary has been suggested, addressed further in Section 4.3.1. Several flow categories and their qualitative justification are as follows. During drought periods, "subsistence" low flows are necessary to provide salinity refuge conditions near the mouths of inflow sources. For low flow conditions not as extreme as drought, the area of lower salinities is somewhat larger, allowing for tolerable conditions for sessile organisms like oysters. Under normal conditions, the main salinity gradient encompasses more of the estuary, and inflow pulses provide inflow variability, conditions thought to be needed to sustain oyster reef health, improve benthic conditions and provide suitable marsh, shellfish and finfish habitat. Very high, infrequent inflows provide episodic loads of sediments, nutrients and organic matter. These relations of the estuary environment to inflow, while plausible, depend on observation, quantification, and analysis.

The responsibilities of the BBESTs are (1) to quantify as many relations depicted in Figure 2.1-2 as feasible from the available information base, which includes the proper characterization of the variables involved, (2) to indicate the associated uncertainties in the relation, which includes statistical measures of variance, and qualitative judgments about the extent of scientific support within the estuarine system being addressed for each of these relations, (3) to assist in the quantitative formulation of goals for each of the elements of the ecosystem depicted in Figure 2.1-1 that are included in the analysis, which may include statistics of achievement, both historically and as a standard of performance. It is important that the BBESTs clearly identify when hypotheses (i.e., assumptions), however plausible, are being invoked as scientific support.

# SECTION 3
# BAY AND ESTUARY DATA RESOURCES AND "STATE METHODOLOGY" TOOLS AVAILABLE TO EVALUATE DATA

Senate Bill 3 provides that the BBESTs in developing flow recommendations must take into consideration all reasonably available science, without regard to the need for the water for other uses, and the BBESTs' recommendations must be based solely on the best science available. As noted in the 2004 SAC report (SAC, 2004), the twin pillars of the scientific method are observation and explication: put another way, data and models. "Models" in this context includes statistical inferences, mechanistic models, and qualitative judgments ("conceptual models"). The BBESTs should, in principle, array all of these sources of information in developing flow recommendations. The purpose of this chapter is to provide a convenient summary of data and models derived from or applied to the estuaries of Texas and which are readily available to the BBESTs. Emphasis is given to the information resources of the Texas Water Development Board (TWDB), because of the breadth and accessibility of its holdings. But it should be emphasized that for a specific estuary there may be additional resources of data or models available from state or federal agencies, from private consultants and engineering companies, and from academic research projects, of which the BBESTs should avail themselves.

Because the TWDB has long recognized the need to include estuary inflow requirements in the State water planning process, the TWDB and the TPWD have been engaged in studies of the estuaries of Texas for nearly half a century, seeking to establish a scientific basis for determining the effects of inflows. Many of the results of this program of study have become elements of the State Methodology, as summarized in Longley (1994), and may be of value to the BBESTs. Table 3-1 identifies the main "tools" available from the State Methodology according to the major category and type of tool. The "tools" are distinguished as being "Data", "Analysis", or a "Model". "Data" refers to raw or processed data sets, many of which are employed in multiple-variable analyses or models. They are only listed once where they first occur. The "Analysis" type refers to an analysis of data (specified in the "Data" column) that generates a mathematical relation, and may arise from, e.g., a mass-budgeting, a statistical regression, formulation of a constraint, or informed judgment. The "Model" type refers to a mechanistic, i.e. deterministic, mathematical formulation of some property (or properties) of the estuarine environment, typically implemented for numerical solution on a computer. These models may also rely upon the data listed in the "Data" column and the results of "Analysis" for complete specification of model inputs. (An "Analysis" in the sense used here is a *statistical* model, which is fitted to measurements. For clarity, the statistical and mechanistic models are differentiated. In practice, any mechanistic model of an estuary includes statistical models within its formulation, so these are hybrid models.) Most of these data sets and models are described more fully in the following sections.

## 3.1 HYDROLOGY

The historical timing and quantity of inflows to Texas estuaries is essential to virtually all subsequent analyses (cf. Figure 2.1-2). Total inflow to an estuary is found by summing the flows measured at streamflow gages, flows below these gages and in ungaged watersheds, diversions

Table 3.1-1 State Methodology Component Data, Analysis, and Models

| Category | Data | Analysis | Model |
|---|---|---|---|
| **Hydrology** | Precipitation, monthly gaged and ungaged inflows | Historical inflow exceedance frequencies | TxRR |
| **Salinity** | Historical TWDB, TPWD, TDH salinity data | Species/inflow regression equations | |
| **Biology** | TPWD Coastal Fisheries abundance data, historical harvest data | Harvest/inflow, Harvest/abundance regression equations | |
| **Hydrodynamics/ Salinity Transport** | Synoptic flow, elevation, salinity data | | TxBLEND |
| **Nutrients** | USGS and TCEQ water quality data, NOAA atmospheric deposition data | Estimated nutrient loads, nutrient budgets for some estuaries | |
| **Sediment** | USGS, TWDB sediment data | Estimated sediment loads | |
| **Optimization** | | MinQSal, MinQ, MaxH inflows | TxEMP |

removed from the ungaged streams and watersheds, and return flows returned to ungaged streams and watersheds or directly into the estuary. Inflows entering the stream below the downstream-most gage and in ungaged watersheds are referred to as “ungaged” inflows. The estuary’s freshwater balance is further affected by the net of precipitation and evaporation at the surface. TWDB has developed and compiled records of these component inflows for all the major estuaries in Texas. The Texas Rainfall-Runoff (TxRR) model has been applied to all ungaged coastal watersheds that contribute runoff to major estuaries in Texas. Combined surface inflows (sum of gaged, ungaged, and return inflows, minus diversions) and freshwater balances (surface inflow plus precipitation minus evaporation from bay) have also been computed. Data on total inflows that occurred prior to 1978 were obtained from earlier TWDB studies in which only monthly data were stored, and thus are available only as monthly values. For periods after 1978, inflows are available with daily resolution.

Data - USGS streamflow, TCEQ diversions and return flows, NWS raingage and NEXRAD rainfall, TWDB evaporation, NRCS land use.

Analysis - Various aggregated or integrated measures of inflow, identification of hydrological events, statistical distributions over time

Models - Texas Rainfall Runoff (TXRR), based upon the SCS curve-number method, is available for ungaged watersheds contributing to all major estuaries.

## 3.2 SALINITY

Salinity is a useful ecological indicator of habitat condition that has been widely collected and analyzed in Texas estuaries. As noted in Section 2.3, salinity is a fundamental estuary parameter representing chemical habitat condition. Its magnitude, which ranges from zero to seawater (unless net evaporation is high, which can result in hyper-saline conditions), is an indicator of the proportion of seawater in the water of the estuary. Because of its properties as a tracer, salinity is essential for calibration of hydrodynamic and salinity transport models.

Data - Salinity can be measured by several methods, which vary in accuracy and convenience. Fortunately, the extreme variability in salinity in an estuary obviates the need for precision in measurement, and several alternative techniques yield approximate values of salinity sufficiently accurate for estuary application. These include chemical analysis of water samples for salts or dissolved solids, conductivity of water sample, and refractive index. An important innovation is field-hardened automated data collection technology employing a small conductivity probe and data logger (or, perhaps, telemetry), which enables the operation of a robot measurement system anchored in the estuary, referred to as a “sonde”. Several agencies have deployed sondes in the estuaries of Texas, some for as long as the last twenty years, to obtain a virtually continuous time series of salinity, including the TWDB, Texas Coastal Ocean Observation Network (TCOON) of Texas A&M—Corpus Christi, the U.S. Geological Survey, and the National Ocean Service, as well as river authorities and academic researchers.

As a component of the State Methodology, TWDB has compiled salinity time-series data from its Datasonde Program, and point measurements primarily from TDH, and TPWD. Sonde records are also available from other agencies or entities such as TCOON, river authorities, and navigational data operations.

Analyses - Desirable salinity regimes for different species, multivariate flow-salinity regressions as a function of inflow for multiple sites in the Texas estuaries.

Models - Numerical solutions to the salt-transport equation. In the State Methodology, this is coupled into the hydrodynamic model TxBLEND, described in more detail below. The Corps of Engineers has applied its RMA series of models to several of the Texas estuaries, and limited application has been made of the EPA EFDC model.

## 3.3 BIOLOGY

Biology includes identification of the key flora and fauna of the estuary, as well as direct measurements of their abundance (e.g., as number of organisms per unit area or per unit volume) as a function of space and time. For vegetational species and sessile animals such as reef builders, their specific distribution within the estuary boundaries over time can be an important index to habitats. Though rarely recognized as key species, the plankton, i.e., minute or microscopic organisms (including bacteria) suspended in the water column, and the benthos, i.e the micro-and macrofauna living in the sediments on the bed of the estuary, are major components of the ecosystem. All of these species have been studied by researchers in universities, and federal and state agencies over the years. Quantitative data on their abundance in time and space are highly variable in completeness, accuracy, period of record, and accessibility. The Coastal Fisheries Division Resource Monitoring Program of the Texas Parks and Wildlife Department (TPWD) is designed to monitor the abundance of higher organisms (primarily nektonic macrofauna) of the estuaries, and is a valuable resource to the state. Since the 1950's, TPWD (or its predecessor agencies) has routinely conducted such sampling in the bays of Texas, and since the mid-1970's the results of the program have been archived in digital format. TPWD biologists perform regular collections using a variety of standard gear types on nearly a daily basis, and count and report everything caught. .This sustained data collection program has provided a virtually continuous record of the larger organisms on the Texas coast for nearly four decades. In addition, TPWD has conducted numerous special studies of more limited observation in space and time to address particular biological issues, and it and its predecessor agencies have made routine collections in several of the Texas bays dating back to the 1950's. Although, the TPWD data files in their original forms are enormous and not easily manipulated for analysis, several tools have recently been developed by TWDB, TPWD, and the Houston Advanced Research Center (HARC) to facilitate use of these data[3].

TWDB has developed species abundance-inflow regression equations for selected animal species found in Texas estuaries. Equations originally were developed using commercial fisheries harvest data, assumed to be a measure of organism abundance in the estuary, thus yielding biomass-inflow equations. Later, abundance-inflow equations were developed. Abundance was based on TPWD's Coastal Fisheries effort-independent monitoring data. Inflows in these regressions were based on hydrology data accumulated over bimonthly periods.

Data - TWDB combined inflows, historical annual fisheries harvest and TPWD-based abundances.

Analyses – Multivariate linear regression equations developed for several selected species for each major estuary in Texas.

## 3.4 HYDRODYNAMIC AND SALINITY MODELS

Numerical hydrodynamic and mass transport models, also known as circulation models, are used to simulate the variation of salinity, flow, and water levels throughout a bay, and have been applied to investigate different inflow scenarios. Only a brief overview of the nature and characteristics of circulation models can be given here. The term "model" strictly refers to the mathematical formulation of a physical relationship. The jargon that has evolved applies the term to a computational scheme implemented on a digital computer, frequently even a specific computer code, e.g., TxBLEND, DYNHYD, POM, and EFDC. Any model is a simplification. The point of departure in modeling is to decide what real-world features should be modeled, and which others will be discounted as irrelevant, or deemed to be beyond the capacity of a particular model formulation. The differences between models lie in how this simplification is achieved,

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[3] See following web sites for information on TPWD data analysis tools:
For major bays: http://midgewater.twdb.state.tx.us/TPWD/tpwd.html;
For minor bays: http://www.tpwd.state.tx.us/landwater/land/maps/gis/ris/catch_rate/index.phtml;
For Galveston Bay: http://www.galvbaydata.org/LivingResources/FisheriesDataPortal/tabid/203 /Default.aspx

i.e. what features are retained and what are sacrificed, and what aspects of the real world the simplified model depicts.

Simplification can be applied at three different levels of formulation: conceptual, mathematical and computational. Generally, the conceptual simplifications are the most transparent and easiest to evaluate because they explicitly state what kinds of features the simplified model will retain. Examples are whether tides are explicitly treated or suppressed by averaging over several tidal cycles, whether the estuary geometry is represented as one-, two- or three-dimensional, and whether density-driven circulations are explicitly treated or implicitly specified by some external parameter. Mathematical simplifications have the objective of expediting the mathematical solution of the problem, while maintaining fidelity to the conceptual model. This level of formulation includes the incorporation of specific mathematical expressions for different processes (which can include some conceptual simplification). Evaluation of a mathematical simplification is obviously more subtle than a simplification at the conceptual level, and may require some sophisticated analysis. Simplification at the third level, the computational, involves approximation of the mathematical expressions to achieve a numerical solution. Theory is uneven, providing only guidance at best, and evaluation is usually empirical, hence case-specific.

Model application requires the specification of boundary conditions. Estuary waters are in contact with the rest of the world, at their surface, at the bottom, around their shoreline, at the entrances to the sea, and at the upstream points of inflow, and various exchange processes operate at each of these boundaries. These must be specified to "close" the solution. Though often treated as an afterthought, the correct specification of boundary conditions is easily half the problem of correctly applying a complex circulation model. Depending upon their characteristics, these boundary conditions may be developed from field data, from statistical relations or from other models. At a minimum the inflows to the estuary, friction at the bottom, stresses at the surface, and tides and salinity at the ocean boundary of the computational area must be specified. Generally these are functions of time, which is a further complication. The complexity of specifying boundary conditions at the estuary inlet(s) to the sea is often obviated by moving the boundary out into the ocean, thereby allowing the hydrodynamics to dictate the exchange at the inlet(s).

The development and application of hydrodynamic/salinity models rely upon an extensive base of field data from the estuary itself. Despite the imposing theory upon which such models are based, there remain "free parameters" in the equations, i.e., variables employed to quantify key processes but whose values must be supplied, such as bed friction coefficients, mixing coefficients (including diffusivities and dispersivities), and wind-stress coefficients. Values of these parameters must be established by a process of trial and error, in which model predictions are compared to field observations, and the parameters adjusted to force agreement. Clearly, the more parameters that must be treated, the more independent sets of data must be available. Moreover, these free parameters are typically site-specific and cannot be transferred from another estuary. This general process of adjusting the free parameters to replicate observed data is referred to as "calibration". Ideally, a model would be further subjected to "verification", in which the model outputs are compared to additional (and independent) sets of data to assess the quality of the model prediction.

TWDB has developed, calibrated, and applied two-dimensional (horizontal) models (circulation and salinity distribution of vertical-mean parameters in the horizontal plane) for all the major estuaries in Texas using the TxBLEND model program (TPWD and TWDB 1998, 2001, 2002, 2004, 2005). Reports describing calibration results are available for the Corpus Christi Bay model (CCBNEP 1997) and for the Galveston Bay model (TWDB 2005). The Lower Colorado River Authority (LCRA) has also calibrated and applied TxBLEND in support of freshwater inflows studies for Matagorda Bay (LCRA 2006). Calibration results quantifying model performance and plots of model versus measurement comparisons for the remaining major estuaries are available from the Bays and Estuaries Team at TWDB. In all cases, model water level and velocity were typically calibrated over shorter periods of a few days, while salinity was calibrated with data over several years. This is a reflection of the lower availability of velocity data and the greater availability of salinity data.

Multi-bay models have also been developed in which adjacent connected bays are incorporated into a single model grid, and output files have been generated in some studies for multi-year simulations. TWDB is also now evaluating three newer generation models (SELFE, FVCOM, and UTBEST) for potential future use. Other agencies have also employed advanced numerical hydrodynamic/salinity models for some of the Texas bays, including in a few cases, three-dimensional models. The U.S. Army Corps of Engineers has made extensive application of its RMA series of models (which includes both two-dimensional and three-dimensional versions) to Sabine Lake, Galveston Bay, Matagorda Bay, Corpus Christi Bay and the Laguna Madre. Research-level models for a few of the estuaries have been developed at several Texas universities.

Data - NOAA bathymetry, NOAA/TCOON tides, NWS rainfall, TWDB evaporation, TWDB inflows, TWDB salinity, water levels and flow.

Models - A TxBLEND model is available for all major estuaries in Texas from the TWDB.

## 3.5 NUTRIENTS

Nutrients can be considered the "food" that drives the estuarine ecosystem and are essential for overall production. Nutrients are measured by standard chemical analyses, almost always on samples of water retrieved from the estuary. For the Texas estuaries, compounds of nitrogen and phosphorus are the nutrients of greatest concern, because they are greatly affected by human activities. Chemical sampling of these compounds has been carried out by a number of federal, state and River Authority/Water District monitoring programs, as well as by academic researchers. Both National Estuary Programs in Texas (Galveston Bay and Corpus Christi Bay) acquired and compiled a combined data base of historical measurements from the various agencies and programs.

The load of a nutrient is its mass transfer into the watercourse. Estimates of long-term average nitrogen loads have been completed by the TWDB for all major estuaries, and phosphorus loads have been completed for most. More complete nitrogen budgets that describe important nitrogen sources (inflows, wastewater loads, atmospheric deposition, release from sediments, tidal influx, etc.) and sinks (denitrification, ammonification, export to Gulf, burial, etc.) were developed for some estuaries, as noted below. Because the data required for developing loads and budgets are limited, they should be considered starting points for further investigation.

Historically, researchers at academic institutions and consulting firms have also assembled nutrient budgets. The two National Estuary Programs in Texas included work tasks that performed nutrient budgeting.

Data - USGS streamflow, TCEQ and USGS water quality, NOAA Atmospheric Deposition Program. water chemistry data collection by various agencies.

Analyses - Estimated nitrogen and phosphorus loads can be provided by the TWDB, including basic nitrogen budgets for some major estuaries (Trinity-San Jacinto, Nueces, Lavaca-Colorado).

## 3.6 SEDIMENT

Sediment, which includes fine-grained solids suspended in the water column, sand-size (and larger) particles and organic debris (seston), play important roles in the estuarine ecosystem. Because some nutrient compounds sorb readily to fine particulates, sediment loads can represent an associated load of nutrients. As physical particles, sediment, when deposited, can support physical habitat. In particular, sediment transported into a delta or marsh by inflows can be important compensation for erosion of the delta surface at high waters and for the effects of subsidence. Sediments can also affect production in the estuary by limiting the vertical penetration of sunlight. Various measures of suspended sediment are routinely monitored, including turbidity, water density, and TSS, and, though they can be interconverted, the conversions are empirical and noisy.

The mass transfer rate of sediment is the sediment load. Estimates of long-term average sediment loads from suspended solids data combined with the appropriate flow have been developed for all major estuaries by the TWDB, as well as by academic and consulting research workers. As with nutrients, data for this purpose is limited, and the estimated loads should be viewed as starting points for further analyses.

Data - USGS streamflow, USGS and TWDB sediment concentration data. Shoreline erosion studies by the Bureau of Economic Geology, of the University of Texas. Data on littoral sediment interception, deposition and dredging from the Galveston District Corps of Engineers. Historical measurements of turbidity by TCEQ, TPWD, and academic researchers.

Analyses - Estimated sediment loads can be provided by the TWDB for Guadalupe Estuary and Laguna Madre. A sediment budget study was conducted for Laguna Madre.

## 3.7 OPTIMIZATION

In the early years (i.e., the 1960's and 1970's), the TWDB Bays and Estuaries Program pursued the idea of defining inflow "needs" of an estuary as the levels of inflows that resulted in a maximum of productivity (as measured by the commercial harvest of key species). The first round of estuary inflow reports, the LP-series dating from the early 1980's, relied upon linear programming to determine this optimum (Martin, 1987), in which the seasonal effects of freshwater inflow variation was captured by defining six independent variables of inflow to be the bimonthly totals (January+February, March+April, etc.). Since then, a provision for optimization has remained in the State Methodology as a major tool. The original Simplex-based linear-programming code has been replaced by a far more sophisticated program, TxEMP, which is an extension of the fully nonlinear optimization program GRG2 (Lasdon and Waren, 1986) to accommodate constraints on all of the input and output variables, as well as levels of probability ("chance-constraints", see Tung et al., 1990). The management-target inflow patterns of MinQ and MaxH (or MaxC) detailed in Longley (1994), are determined by application of TxEMP. The TxEMP optimization model is one means of combining information on inflow, salinity, harvest or productivity (measured as harvest biomass or as abundance), nutrients, and sediments to achieve specific objectives related to flow, salinity, and harvest or productivity.

Analyses - TWDB salinity-inflow regression equations, TWDB species-inflow regression equations, TWDB inflow hydrology, species- and location-based salinity constraints, nutrient and sediment constraints, all employed as inputs to TxEMP.

Model - TxEMP optimization solutions for all major estuaries in Texas for the problem statements *minQ*, *maxH* (or *maxC*) and *minQ-sal*. See Longley (1994) for the technical definition of these problem statements.

# SECTION 4
# METHODOLOGIES FOR DEVELOPING BAY AND ESTUARY FRESHWATER INFLOW RECOMMENDATIONS

There is a variety of methodologies that could be used to develop freshwater inflow recommendations, as surveyed in two recent reviews of approaches to the problem (Alber 2002, Esteves 2002). These and several other methods were summarized in the 2004 SAC report (SAC, 2004). In this chapter we focus on only those methods that have been historically applied in Texas estuaries, or in principle could be applied with modest effort because the information resources required are generally available.

The conceptual model for the recommended approach is diagrammed in Figure 2.1-2. To summarize Section 2 of this report, a methodology is determined by: (1) the variables in this diagram, proceeding from left to right, that are explicitly addressed; (2) how these variables are characterized, i.e. how they are measured and how the measures are processed in space and time; and (3) what goal(s) are sought to be achieved in the ecosystem by dictating the inflow "regime". While the causal effects of flow are directed: inflow → salinity → biology, the specification of a necessary inflow requires addressing the converse problem. First, the biological resource to be protected is identified. Second, the habitat requirements of that resource, including but not limited to a salinity range, are identified in both space and time. Third, the flow regime needed to support these requirements, e.g. a required distribution of salinity, is determined, based upon either statistical analysis of field data or mechanistic salinity-transport models. When information is absent on biological resources, or their biochemical requirements, this process may have to be truncated.

Because of the complexity of the relationship between flow and biology of a watercourse, and the difficulty of establishing it, approaches have been developed that rely solely on protecting the inflow hydrological regime, assuming that if the flow were maintained in some historical fashion, then the biology would be taken care of. This is the basic foundation that underlies the IHA (The Nature Conservancy, 2007, Richter et al., 2006, see Section 4.4.1 below), HEFR (see Section 4.3.1 below), NWF Inflow Pattern (see Section 4.3.2 below), and Percent of Flow (see Section 4.4.3) approaches. Historical hydrological patterns, particularly seasonal, also play an important role in applications of the State Methodology (Section 4.1, below), the Salinity Zone (Section 4.2), and the LCRA-SAWS Inflow Criteria (Section 4.4.2 below) methods, but, to varying degrees and levels of sophistication, other factors and relationships pertaining to salinity, species abundance or productivity, nutrients, water quality, and/or sediment loadings also are incorporated into the decision process for determining freshwater inflow requirements.

In presenting candidate methodologies in this section, we summarize the methodological approach including the information resources exploited, and indicate how the method corresponds to a specific implementation of the simplified relationships depicted in Figure 2.1-2.

## 4.1 STATE METHODOLOGY

### 4.1.1 General Procedure

The Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD) are responsible for determining the total inflow to each bay necessary "...for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent," referred to as "beneficial inflows" [Texas Water Code §11.147]. This determination involves a two-step process. The first step, conducted by the TWDB, is the application of a quantitative methodology to determine optimal inflows to the bay under consideration that will achieve specified management "goals". The second step, conducted by the TPWD, is to select that inflow solution, among the several determined by TWDB, considered to best achieve the purpose of maintenance of ecological health and productivity. The method employed in the first step (by the TWDB) is referred to as the State Methodology, and that of the second step (by the TPWD) is referred to as "verification analysis." This is the terminology employed in the 2004 SAC report (SAC, 2004), and the terminology observed here. However, it should be noted that sometimes "State Methodology" is applied to the combined two-step procedure. In the present section the TWDB State Methodology is described. The TPWD Verification Analysis is addressed in Section 4.2.

The State Methodology is documented in an extensive report (Longley 1994), consisting of many components of study, data compilations and analyses, and modeling (see SAC, 2004, and Section 3 above). The final answer is a sequence of monthly flows to the estuary that will achieve a specified "goal". Central to the inflow determination are two sets of relationships: salinity at selected locations in the estuary as a function of inflow, and abundances of several key species as a function of inflow. Both of these are determined by a statistical fit to data. For the salinity relation, a multivariate linear regression is used on two independent inflow variables, the monthly-mean flows corresponding to, and preceding, the date of salinity measurement.

More important is the relation of abundance of a key species on inflow. In Figure 2.1-2, this represents the direct relation between "inflow" and "biology" depicted by the bold broken arrow. Abundance is measured in two ways in the work of the TWDB. In the early analyses of major estuaries, when commercial harvest was the only long-term species information available, commercial harvest was used as a surrogate for abundance. This assumes in effect that harvest is primarily dependent upon the population density of the organisms in the bay. With the increasing data base of directly measured abundance data from TPWD, this assumption could be tested. This dependence has proven to be weak because other variables affect, and even dictate, the commercial catch, not the least of which is economics. In later estuary analyses, abundance based upon the TPWD Coastal Fisheries database has been used. The key species vary with the estuary; they are summarized in Table B-1 of Appendix A for the major bays.

The regression equations intended to reflect dependence of species abundance on seasonal variation in inflow, therefore the characterization in inflow must exhibit seasonality. Inflows were aggregated into bimonthly periods, as follows:

$Q_{JF}$ - January + February

$Q_{MA}$ - March + April

$Q_{MJ}$ - May + June

$Q_{JA}$ - July + August

$Q_{SO}$ - September + October

$Q_{ND}$ - November + December

This is an example of cyclical (or calendar period) inflow characterization, described in Section 2.2.1 above, because the inflow aggregation is locked into the calendar. The statistical models used are multivariate linear regressions in which each of these bimonthly flows is a separate independent variable.

The last substantial step of the State Methodology process is to employ the salinity and key species regressions in a sophisticated nonlinear multivariate optimization model called TxEMP, described in Section 3.7, to determine the distribution of monthly inflows that either maximizes or minimizes some variable, defined by a specific management "goal". The most important of such goals are:

| | |
|---|---|
| *maxH/maxC* | total annual harvest/abundance is maximized, subject to constraints on inflows |
| *minQ* | total annual inflow is minimized, subject to the constraint that total annual harvest be no lower than 70% of its period-of-record average, and subject only to constraints on salinity |

In addition, solutions are sometimes provided for *maxQ* and *minQ-sal*, and additional potential goal formulations are given in Longley (1994). Both *maxH* and *minQ* monthly flows are shown in Figure 4.1-1 for Galveston Bay. The TxEMP solutions for all of the major bays are summarized in Table A-4 in Appendix A.

The "constraints on inflow" in the above definitions of *maxH* and *minQ* are an important feature of the TxEMP solution. Because the functions being optimized, *viz*. the abundance-versus-inflow regression equations, are monotonic they do not exhibit a local optimum. In order to achieve such an optimum, bounds must be imposed. These bounds are input into the TxEMP solution as "constraints" on the answer. The inflow constraints for all of these solution goals are that each of the bimonthly and monthly inflows must lie between the lowest decile and the median for that month/bimonth. Additional constraints related to salinity, ratios of species abundances, and other factors are also applied. These constraints represent a combination of both policy and science decisions, and can be modified as information related to policy or science changes.

In terms of the conceptual model of the inflow determination process, Figure 2.1-2, the State Methodology employs *both* a salinity relation, with salinity viability limits that represent the aggregated salinity bounds for key species selected for the estuary, and a *direct relation* of species abundance to inflow. In principle, the State Methodology also includes requirements for nutrient transport and sediment loading (see Appendix A). However, in practice, the requirement is to maintain average historical loads, and satisfaction of the biological "productivity" and salinity “viability limits” goals of the method have been found to provide at least the annual historical loads of sediment and nutrients, so these conditions have no effect on the final answer.

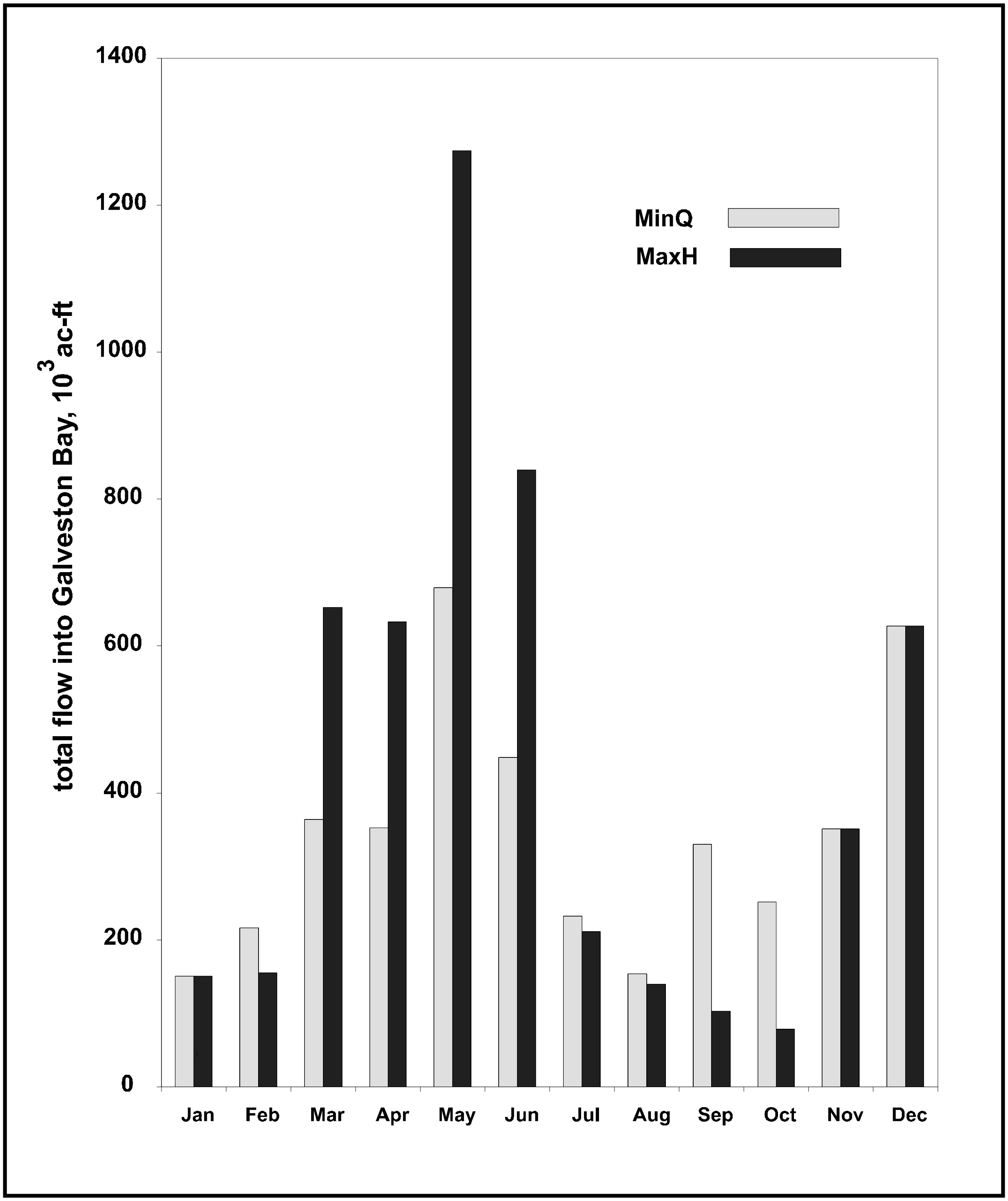

Figure 4.1-1 - TxEMP Inflow Solutions for Galveston Bay

### 4.1.2 Strengths and Weaknesses

Strengths of the State Methodology include:

- *Easily understood objectives* - The harvest/abundance goal of maintaining a minimum abundance/harvest as a fraction of the historical mean of "economically important and ecologically characteristic sport or commercial fish and shellfish" is clearly understood.
- *Sensible way to integrate disparate information* - TxEMP integrates management goals with hydrological and biological goals and constraints.
- *Attempts to make best use of flow resource* - TxEMP computes the minimum flows that meet goals and constraints.
- *Constraints keep solution "reasonable"* - Hydrological and biological constraints keep the solution "reasonable". Salinity zones are evaluated for important habitat areas as a final check. Although the optimization may be weak due to nature of harvest equations, reasonableness of the solution is enforced by constraints.
- *Optimization model is objective* - Solution found after goals and constraints are set is objective.
- Solutions have been obtained for each of the major estuaries of the State and are available in an appendix to the TPWD verification reports.

Weaknesses of the State Methodology include:

- *Commercial harvest data subject to numerous sources of error and are affected by factors having no relation to abundance* - Fishing effort, reporting of catch, and other issues affect accuracy of reported harvest can undermine the use of harvest as a representation of abundance. Moreover, harvest may not have occurred in the system where it was sold at dockside.
- *Low predictive ability of harvest/abundance equations* - Predictive ability of harvest/abundance equations is low, although this is not surprising due to the complexity of the ecological relationships between flow and harvest/abundance.
- *Species may not fully represent estuarine ecology* - Initial applications of the State Methodology focused exclusively on commercial species (mainly because harvest data records provided the only sufficient record of species information). As extended periods of TPWD fisheries independent data became available, more recent applications have included one or two species of ecological, but not commercial, significance.
- *Solution implies that flows must always be met* - While the goal of determining flows to meet targets is met by the State Methodology, the solution calls for the flows to always to be met. That is, there is no attainment strategy, such as a statistical frequency of occurrence. Moreover, the *maxH* and *minQ* patterns do not occur, even approximately, in the historical inflow record to the estuary.

- *Does not address low flow needs explicitly*. This is because low flows do not arise as optimum solutions as long as there is a biological constraint, or biology is the objective function.
- *Does not provide an inflow regime consistent with the requirements of Senate Bill 3* that reflects seasonal and yearly fluctuations, including the required frequency of various inflow amounts or inflow patterns needed during very dry periods, as well as the frequency of higher inflows during wet years that help sustain a healthy bay and estuarine ecosystem
- *The optimized solution is dominated by the constraints*, e.g. that each monthly or bimonthly flow must lie between the decile and median values, which are specified without scientific defense. While constraints are a necessary and important aspect of the optimization problem specification because they ensure that the solution is realistic, when the majority of the resulting monthly flows are the constraint values, these constraints are, in effect, the answer, and therefore the basis for their specification becomes central.

## 4.2 SALINITY ZONE APPROACH

### 4.2.1 General Procedure

The salinity-zone approach assesses the suitability of the distribution of salinity within an estuary for a specific organism. By "within an estuary" is meant some measure of the geographical extent of various ranges of salinity, or even their specific geographical location(s). It therefore is a combination of salinity-preference/tolerance limits and salinity mapping, and requires data depicting both classes of information. As noted elsewhere, salinity can be important to the biological functioning of estuarine organisms, though almost by definition such estuarine organisms are also able to withstand, and even thrive in, a wide range of salinities. Nonetheless, much effort has been invested in determining the ranges of salinities for individual species that are "preferred", some of which is summarized in Longley (1994). If such an "optimum" range of salinity can be defined for an organism, then the next task is to determine the geometrical configuration of those salinities in the estuary. Typically, this is based upon field data that are displayed in a geographical format, e.g., as a distribution of isopleths of equal salinity ("isohalines"), on which the water enclosed by the isohalines corresponding to the bounds of the optimum zone is identified. This salinity-optimum region can be quantified by the area or volume enclosed between the isohalines. A more sophisticated approach is to determine how this optimum salinity zone overlays other habitat features considered to be important to the organism in question, such as water depths, bed characteristics, vegetation, or marsh habitat.

Because this approach is based upon the display and analysis of two combined sources of information, viz. salinity preference zones for the organism, and empirical patterns of salinity in the estuary, it may be considered a derivative of other analytical approaches. Its novelty is in the geographical display of the salinity information within the estuary in a form that is relevant to the organism of concern, a procedure that is greatly facilitated by the use of Geographical Information Systems (GIS) methods. This method thereby affords a means of (perhaps) interpreting the observed abundance density of that organism in view of the salinity regime obtaining when the abundance observations were made.

The link to freshwater inflow is through its control on salinity distribution. With empirical isohaline patterns, the corresponding measurements of total inflow to the bay must be determined from hydrological and climatological data (see Section 3.1). Only those flow regimes for which salinity data exist will be represented in this analysis. A separate issue is how to extend the analysis to inflow levels for which data may not be available. If there are data-based salinity depictions for a wide range of inflows, it may be possible to infer the salinity patterns for other inflows by interpolation, extrapolation or more sophisticated regressions.

An alternative is to employ the predictions of salinity from a hydrodynamic/salinity-transport model at a specified inflow regime. This, of course, assumes that a suitably formulated and adequately validated model is available to the analyst.

A prominent example of the salinity zone approach is the "verification analysis" carried out by TPWD in which the results of the TWDB-application of the State Methodology (Section 4.1) are compared to field observations of the occurrence of representative species in the estuary. The TPWD undertakes a separate evaluation to select among the flows obtained from the State Methodology for different management goals, principally the *maxH/MaxC* and *minQ*. The TPWD "verification" procedure generally consists of:

1. Use of the simulated time series of salinity in key areas of the bay, produced by the hydrodynamic circulation model TXBLEND to choose the flow regime that produces the most favorable salinity range.

2. Application of the TPWD Coastal Fisheries data for selected species to determine the spatial distribution of abundance in the bay, and its association with salinity distribution.

3. Application of the simulated salinity distributions from TXBLEND to examine the areas enclosed with the preferential salinity range for an organism, those flow regimes with maximal areas being considered preferable.

Other conditions specific to the individual estuaries, such as instances of oyster disease, increased predation by marine organisms, and marsh inundation, may be invoked as further ecological and scientific lines of evidence in support of the selection of inflow regime options.

TPWD performs a GIS-based analysis to evaluate the association of average abundance of various species with average field measurements of salinity, then uses TxBLEND-modeled salinity distributions under *minQ* and *maxH*/*maxC* inflow scenarios to determine how the acceptable salinity zones from the abundance analysis compare to model projections. An example of the GIS-based analysis of abundance-salinity association for two species in Galveston Bay is shown in Figure 4.2-1. Though the period of years over which the average abundances and salinities are computed is the same (1982-93), the ranges of months differ, so the isohaline distributions are different. Figure 4.2-2 shows the GIS-determined observed salinity distribution and TxBLEND model results for Sabine Lake, on which is superimposed the distribution of various marsh habitat types.

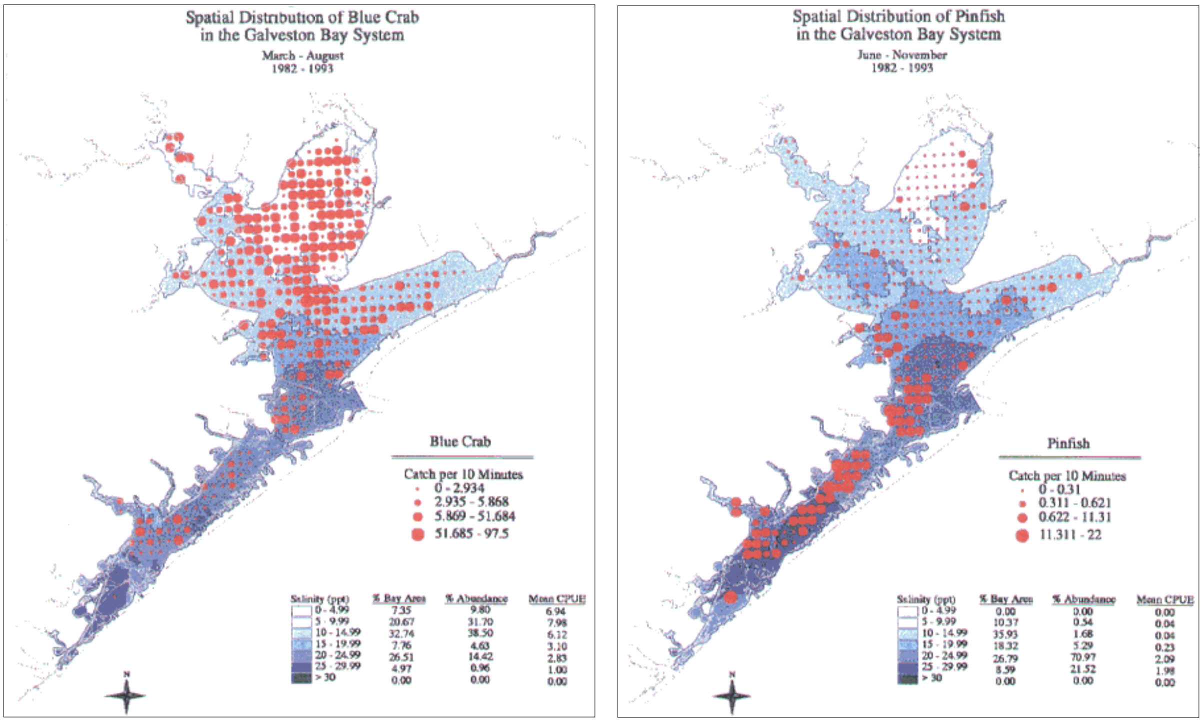

**Figure 4.2-1 Abundance of Blue Crab and Pinfish in Galveston Bay Superposed on Averaged Salinity Distribution**

With respect to the diagram in Figure 2.1-2, the salinity-zone approach is based entirely upon the relation inflow → salinity → biology, in which a desirable salinity zone is based upon the occurrence (or preference or tolerance) range of a key species, and this salinity zone is characterized by its area of occurrence within the estuary. The management goal is derived from the identification of the target species, and literature and/or experimental determination of the salinity range occupied by that species. In the case of the TPWD verification analysis, only the optimum solutions *maxH/maxC* and *minQ* of the State Methodology are addressed (which, as noted in Section 4.1, are presented without recommended statistics of attainment). Because these optimum flow patterns do not occur in the historical hydrology, it is not clear how an attainment statistic can be prescribed.

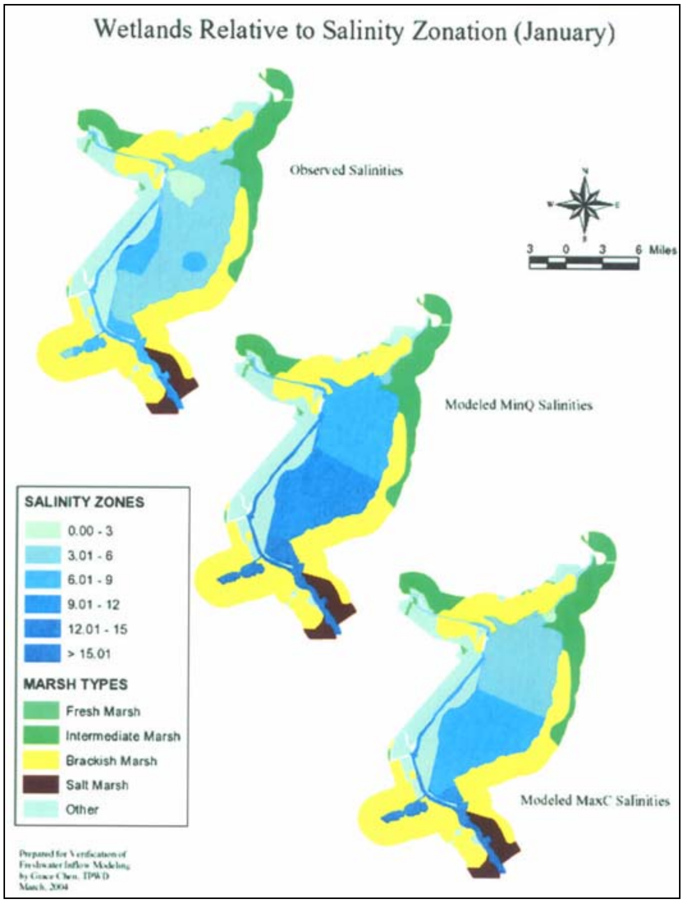

**Figure 4.2-2 Observed Mean Salinity and TxBLEND-Predicted Salinity Zones Compared to Locations of Marsh Habitat Areas**
(from Sabine Lake TPWD Verification Analysis)

### 4.2.2 Strengths and weaknesses

Strengths of the salinity zone approach:

- Provides quantitative measure of the extent of the desirable salinity range within the estuary.
- Is not as sensitive to minor variations in inflow and associated isohaline locations
- Allows capability to combine salinity zone with other geographical features of the estuary, e.g. shallow-water zones, marshes, etc.
- Affords graphic display capability to easily communicate results

Weaknesses of the salinity zone approach:

- Extremes of flow may not be well represented in either the data or model results to supply meaningful statistical evaluations.

- Is dependent upon the accuracy with which isohaline patterns may be delineated.
- In the case of the TPWD verification analysis, is based upon TxBLEND-generated isohalines, which is not yet a well-validated model. (Note that the calibration results support the use of TxBLEND for this purpose, validation of the model is in progress, and that other models could equally well be used.)

## 4.3 HYDROLOGY-BASED APPROACHES

### 4.3.1 Hydrology-Based Environmental Flow Regime (HEFR) Method

The Hydrology-Based Environmental Flow Regime (HEFR) method is a new, relatively flexible computational approach for developing a flow regime matrix that is consistent with the Texas Instream Flow Program in the sense that it identifies multiple flow regime components and hydrologic conditions across different months, seasons, or years. Presented herein is a brief summary of HEFR. Additional details can be found in SAC (2009a).

The primary goal of HEFR is to identify a reasonable schedule of flow components that are adequate to protect a sound ecological environment. For instream applications, this is largely predicated on identifying important flow components (e.g., subsistence flows, baseflows, high flow pulses, and overbank events), understanding the ecological roles provided by those components (e.g., high flow pulses may provide spawning cues; see also §2.2 of SAC (2009a) and Table 1 of Richter et al. (2006)), and quantifying reasonable facsimiles of those historically-observed components for inclusion in an environmental flow matrix recommendation. For an application of HEFR to bays and estuaries, analogous flow components, with associated ecological roles, have to be identified. Depending on those components and roles, it is possible that a careful selection of HEFR parameters could generate meaningful results[4]. It is also possible that additional flexibility would have to be coded into HEFR to provide the appropriate flow components and characteristics.

With respect to the diagram in Figure 2.1-2, only the inflow component is considered in HEFR. This therefore represents the "default" state of the process to be employed only when there is no base of information on either the habitat features of the ecosystem, or its biology (see Section 2.5).

#### 4.3.1.1 General Procedure

HEFR is based solely upon hydrologic data and computes simple summary statistics of individual flow regime components. HEFR begins with the selection of a flow gage and a period of record. The next step in HEFR is to separate the hydrograph into appropriate flow components (based on identified ecological roles of the components). HEFR offers two options to separate the daily hydrograph, the IHA and MBFIT, discussed in detail in SAC (2009a). This parsing results in each day of the hydrograph being classified as one of up to five flow regime

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[4] Recent modifications to HEFR, including increased seasonal flexibility, alternative calculation methodologies for hydrographic separation and episodic events, and flexible percentile assignments, have greatly increased the flexibility of HEFR. These recent enhancements to the HEFR program are described in the Instream Flow SAC report (2009a) dated April 20, 2009.

components that correspond generally to the TIFP regime protocols (TCEQ et al., 2008), an example of which is shown in Figure 4.3-1. We note that in the instream environment the individual storm hydrographs are considered to be important, whereas in the estuary environment there is considerable integration, both in the inflow signal and in the response of estuary condition (e.g., salinity) and biology. Therefore, it is not clear that the specific storm events have an ecological significance in the estuary comparable to their role in the stream.

While HEFR was originally conceived as a tool to develop instream flow recommendations, it could also be appropriate for freshwater inflows to estuaries. For application to an estuary, a daily flow record is required for inflows to the estuary. Such a record can be created from the daily data at the lowest USGS gages on each of the principal inflowing rivers, which can be further augmented by TxRR output for ungaged areas. As summarized in Section 3.1, TxRR results are available from TWDB at a daily resolution for recent simulation periods, and monthly back to around 1941 (in some cases earlier). (Diversion and return flow data generally are monthly only, but typically these do not vary appreciably from day to day, so they could be added as a daily rate computed from the monthly values.)

As an example of this kind of application, a provisional HEFR application was made to the total inflow record for San Antonio Bay, in which the sum of the daily gaged flows of the San Antonio (Goliad) and Guadalupe (Victoria), the summed TxRR daily runoff simulations for ungaged areas, and the net return flows – diversions (converted to a daily rate from monthly data) for the period 1977-2005. For this case study, the HEFR algorithms were run with the IHA hydrograph separation program, using the default values listed in Appendix A of SAC (2009a), except that the winter season was specified to start in January. This change allowed the wet spring months of April, May, and June to be grouped together into one season. Also for this case study, no attempt was made to identify estuary-specific flow components or ecological roles, as would be necessary in a more formal HEFR simulation in an estuarine context. The resulting HEFR matrix is shown in Figure 4.3-2.

While the San Antonio Bay case study presents some graphical comparisons of results from the State Methodology and from the HEFR-based approach for developing instream flow recommendations, it is not considered to be a comprehensive presentation of this subject nor a full demonstration of how HEFR might be applied to assess freshwater inflow requirements for an estuary. Still, there is information that may prove to be useful not only with regard to reconciling differences in riverine instream flow recommendations and estuarine freshwater inflow recommendations, but also possibly with establishing a common approach for developing estimates for both types of aquatic systems within the timeframe of Senate Bill 3.

#### 4.3.1.2 Strengths and Weaknesses

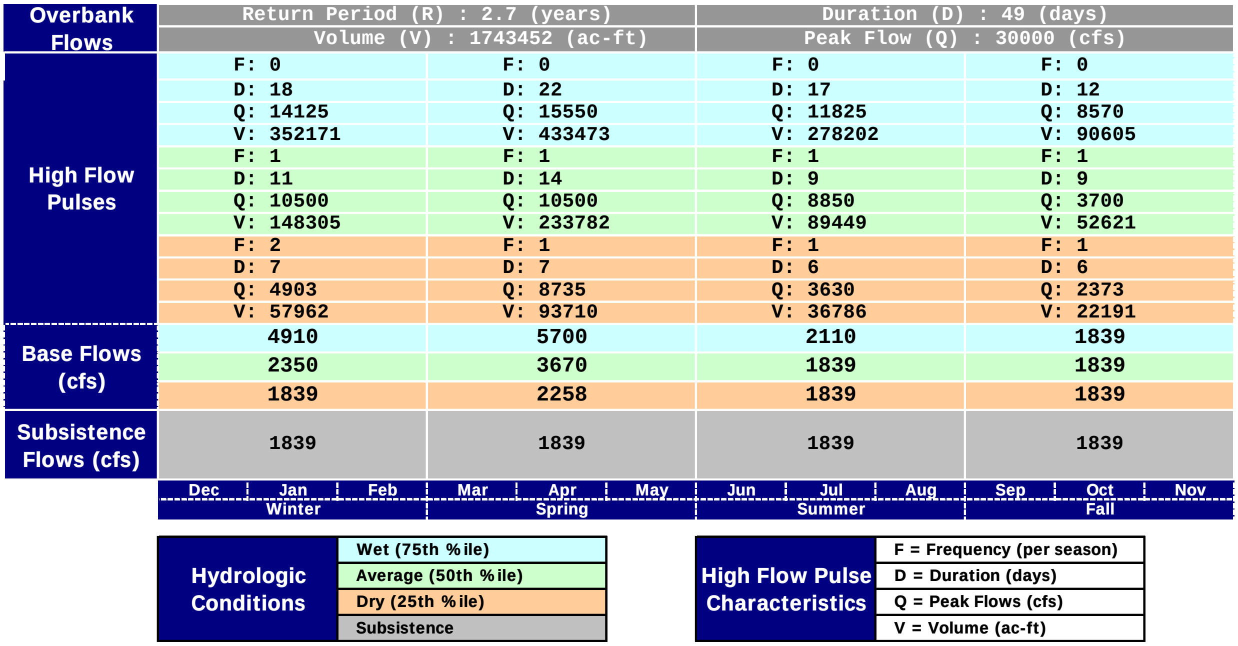
Strengths of HEFR include:

- Hydrologic data are relatively robust and consistent at multiple locations, compared to other potential datasets. HEFR shares this strength with other hydrologic methods.

- Hydrology has been considered the master variable in regards to environmental instream flows and may also be considered a very important variable with regards to estuarine inflows. HEFR shares this strength with other hydrologic methods.
- HEFR is computationally efficient, allowing for repeated tests and exploratory analyses.
- There is significant flexibility in setting parameters to parse the hydrograph as well as summary statistics of the flow regime components.
- HEFR outputs have the same format as expected results from the TIFP studies.
- HEFR provides an initial set of recommendations that reflect key aspects of the natural flow regime including multiple flow components and hydrologic conditions (Poff et al., 1997).

Weaknesses of HEFR include:

- HEFR is largely designed to mirror some fraction of historical hydrology and is not based on a defined flow alteration - ecological response relationship. In a similar vein, HEFR has not been validated against biological, geomorphological, and water quality data. HEFR shares this weakness with other hydrologic methods.
- HEFR is not suitable where hydrologic data are lacking and cannot be synthesized. HEFR shares this weakness with other hydrologic methods.
- There is no track record of application of HEFR, especially in an estuary setting, and there are few precedents for some of the decisions that must be made.
- HEFR would not provide useful results in minor bays or lagoons with little inflow.

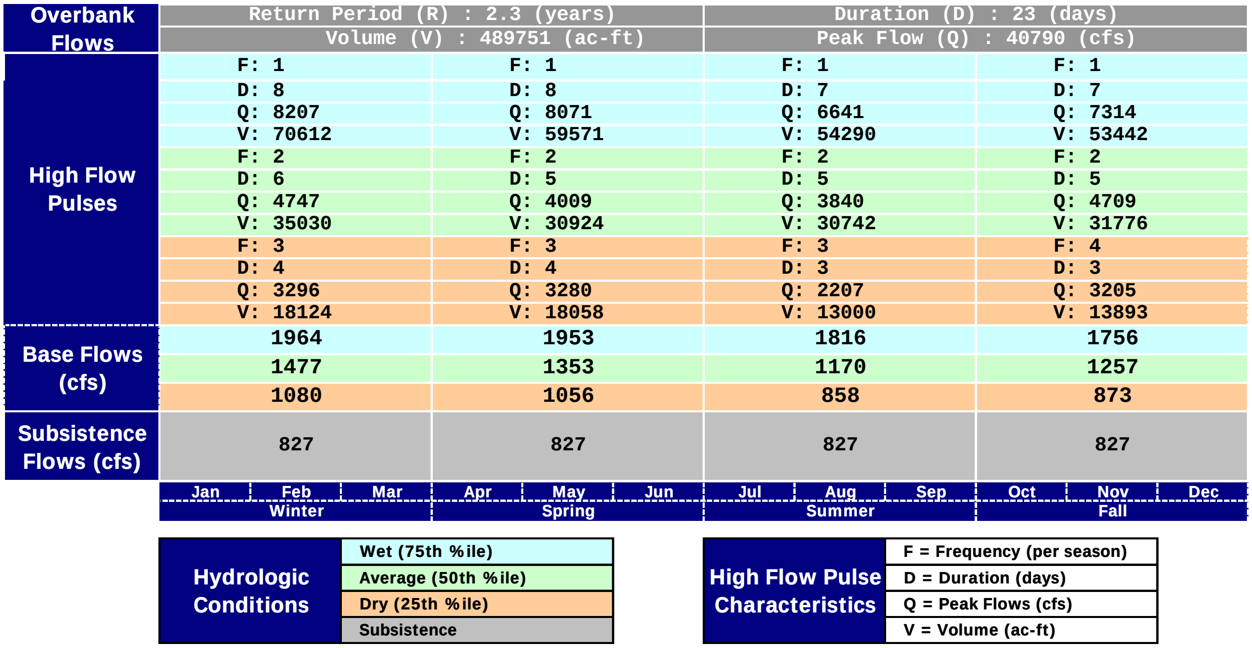


| Overbank Flows | Return Period (R) : 2.7 (years)<br>Volume (V) : 1743452 (ac-ft) | | Duration (D) : 49 (days)<br>Peak Flow (Q) : 30000 (cfs) | |
|---|---|---|---|---|
| High Flow Pulses | F: 0<br>D: 18<br>Q: 14125<br>V: 352171 | F: 0<br>D: 22<br>Q: 15550<br>V: 433473 | F: 0<br>D: 17<br>Q: 11825<br>V: 278202 | F: 0<br>D: 12<br>Q: 8570<br>V: 90605 |
| | F: 1<br>D: 11<br>Q: 10500<br>V: 148305 | F: 1<br>D: 14<br>Q: 10500<br>V: 233782 | F: 1<br>D: 9<br>Q: 8850<br>V: 89449 | F: 1<br>D: 9<br>Q: 3700<br>V: 52621 |
| | F: 2<br>D: 7<br>Q: 4903<br>V: 57962 | F: 1<br>D: 7<br>Q: 8735<br>V: 93710 | F: 1<br>D: 6<br>Q: 3630<br>V: 36786 | F: 1<br>D: 6<br>Q: 2373<br>V: 22191 |
| Base Flows (cfs) | 4910 | 5700 | 2110 | 1839 |
| | 2350 | 3670 | 1839 | 1839 |
| | 1839 | 2258 | 1839 | 1839 |
| Subsistence Flows (cfs) | 1839 | 1839 | 1839 | 1839 |
| | Dec Jan Feb | Mar Apr May | Jun Jul Aug | Sep Oct Nov |
| | Winter | Spring | Summer | Fall |

| Hydrologic Conditions | |
|---|---|
| | Wet (75th %ile) |
| | Average (50th %ile) |
| | Dry (25th %ile) |
| | Subsistence |

| High Flow Pulse Characteristics | |
|---|---|
| | F = Frequency (per season) |
| | D = Duration (days) |
| | Q = Peak Flows (cfs) |
| | V = Volume (ac-ft) |

Figure 4.3-1 Example Flow Regime Matrix for the Neches River at Evadale



| | Winter | Spring | Summer | Fall |
|---|---|---|---|---|
| **Overbank Flows** | Return Period (R) : 2.3 (years)<br>Volume (V) : 489751 (ac-ft) | | Duration (D) : 23 (days)<br>Peak Flow (Q) : 40790 (cfs) | |
| **High Flow Pulses** | F: 1<br>D: 8<br>Q: 8207<br>V: 70612 | F: 1<br>D: 8<br>Q: 8071<br>V: 59571 | F: 1<br>D: 7<br>Q: 6641<br>V: 54290 | F: 1<br>D: 7<br>Q: 7314<br>V: 53442 |
| | F: 2<br>D: 6<br>Q: 4747<br>V: 35030 | F: 2<br>D: 5<br>Q: 4009<br>V: 30924 | F: 2<br>D: 5<br>Q: 3840<br>V: 30742 | F: 2<br>D: 5<br>Q: 4709<br>V: 31776 |
| | F: 3<br>D: 4<br>Q: 3296<br>V: 18124 | F: 3<br>D: 4<br>Q: 3280<br>V: 18058 | F: 3<br>D: 3<br>Q: 2207<br>V: 13000 | F: 4<br>D: 3<br>Q: 3205<br>V: 13893 |
| **Base Flows (cfs)** | 1964 | 1953 | 1816 | 1756 |
| | 1477 | 1353 | 1170 | 1257 |
| | 1080 | 1056 | 858 | 873 |
| **Subsistence Flows (cfs)** | 827 | 827 | 827 | 827 |
| | Jan Feb Mar | Apr May Jun | Jul Aug Sep | Oct Nov Dec |

| **Hydrologic Conditions** | |
|---|---|
| | Wet (75th %ile) |
| | Average (50th %ile) |
| | Dry (25th %ile) |
| | Subsistence |

**High Flow Pulse Characteristics**

F = Frequency (per season)
D = Duration (days)
Q = Peak Flows (cfs)
V = Volume (ac-ft)

Figure 4.3-2 Example Flow Regime Matrix for Total Inflows to San Antonio Bay

### 4.3.2 NWF Inflow Pattern Approach

The National Wildlife Federation has developed a method called an "inflow pattern" approach for establishing some portions of an estuarine inflow regime. While it is generally acknowledged that freshwater inflows to an estuary play the important roles of governing salinity and delivery of sediments and nutrients (e.g. Ward and Montague 1996), the NWF approach focuses on specific naturally-occurring inflow patterns that appear to be important for the estuary. This concept is not unique to the NWF inflow pattern approach, as it also provides the framework for the "freshet" definitions that are utilized in the LCRA-SAWS Inflow Criteria Method (see Section 4.4.2).

Although the inflow pattern approach is primarily hydrologic, utilizing the historic or "natural" inflow record[5], it also relies on physical, biologic, and chemical (salinity or nutrient) lines of evidence, to the extent such information is available, to identify key inflow events which support key ecosystem functions. An explicit goal of the inflow pattern approach is to maintain the timing, magnitude, duration, and frequency of these key inflow events within some reasonable range of departure from their historical or natural occurrence levels.

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[5] The historic record can be used unless there is evidence that watershed alterations have been large enough such that the timing, magnitude, duration, or frequency of certain key inflow events has been seriously modified. In such a case, either a pre-development portion of the historic record, if of sufficient duration, or synthesized inflow record such as the naturalized flows associated with the Texas water availability models can be used as the starting point for the analysis.

The inflow pattern approach is an estuarine application of the "natural flow paradigm" originally developed for stream and river settings (Poff et al. 1997). This paradigm is focused on maintaining reproductive and other biologic processes for fish, invertebrates, and other organisms that are heavily influenced by naturally-occurring seasonal patterns of flow[6]. Although the derivation and application of the natural flow paradigm is rooted in river and stream settings, with limited application to estuaries (e.g. Mattson 2002), there are also strong indications of the ecological importance of certain reoccurring inflow patterns for Texas estuaries. For instance, several studies have found positive correlations between the abundance of several shellfish and fish species and higher inflows in the spring to early summer (LCRA et al. 2006, TPWD and TWDB 2002). Another common Texas freshwater inflow pattern is a low flow period in the summer to early fall which can have deleterious effects on oysters. Oyster predators and diseases are amplified due to the coincidence of these high salinity periods with higher summer water temperature (see Cake 1983 for a summary). Thus, the underpinning of this approach is that there are important, identifiable features of the natural flow regime, including intra-annual and year to year variability, which are essential for ecosystem processes.

Also noteworthy, the term "natural" as used in this connotation does not imply that maintaining fully natural flows is the goal. Rather, it indicates that natural patterns, with regard to the timing, frequency, duration, and magnitude of key events should be maintained within some reasonable degree of departure.

As illustrated in Figure 4.3-3, the inflow pattern approach involves three-steps to identify certain key seasonal patterns of inflow to Texas estuaries that may comprise some portion of an overall estuarine inflow regime.

First, key inflow patterns (or events) which hold particular ecological relevance are identified through a combination of hydrological, biological, and/or chemical lines of evidence. Second, after these key patterns are identified at a general level, it is necessary to detail a specific criterion through a combination of some or all of the following attributes: inflow timing, inflow volume, event frequency, event duration. Not all of these attributes will be necessarily appropriate for the various criteria that may comprise an overall estuary inflow regime. For example, a very low inflow, analogous to the subsistence flow value in the SAC's Instream Flow document (SAC, 2009a), may be focused on maintaining salinity at some tolerable level in a limited area to serve as a refuge for key species. Thus, it will have a volume and frequency of occurrence specified, and perhaps a maximum duration, but likely will not have specific seasonal attributes. Similarly, an extremely high inflow, which could be important for sediment transport and marsh and delta maintenance, may be a short-duration, low-frequency event focused on flow rate that can occur at anytime of the year. Other portions of the inflow pattern may have more constrained timing (season) and volume attributes, such as a spring inflow pulse as discussed below.

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[6] This was termed "biological relevance" by Richter et al. (1996) and "ecologically relevant" by Richter et al. (1997) with regard to the natural flow paradigm for river and stream settings.

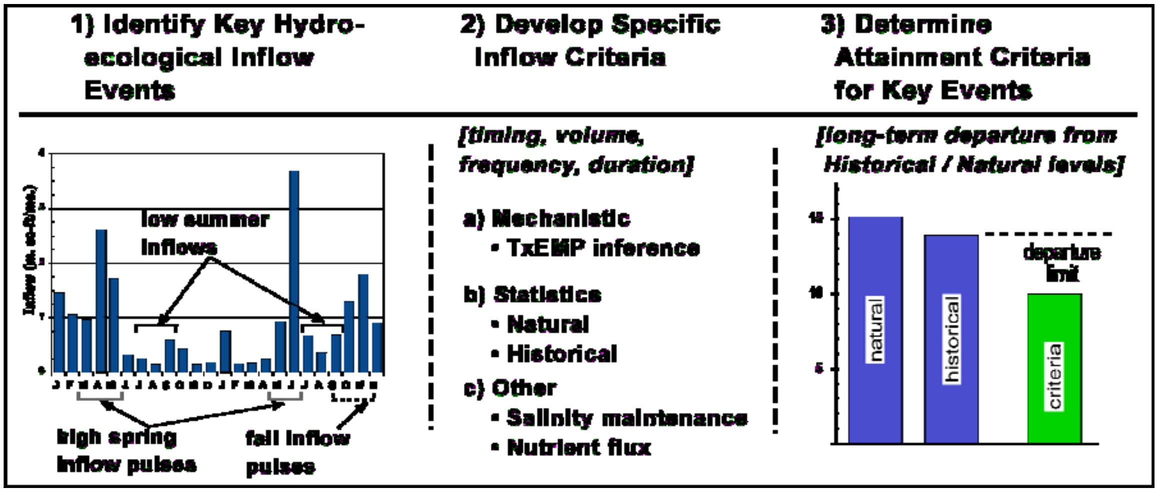


**Figure 4.3-3 NWF's Method for Assessing Freshwater Inflows to Texas Estuaries**
(Note: The inflow sequence shown in the left panel represents a possible pattern of inflow to Texas' estuaries.)

Choosing the specific values of these attributes may rely upon several types of information as shown in the middle panel of Figure 4.3-3. For instance, a criterion aimed at addressing the needs of a low or low-base level inflow, analogous to the dry period base flow in the SAC's Instream Flow document (SAC, 2009a), could utilize purely statistical values, such as the 25th percentile of historic or natural inflow for some or all of the months. By comparison, a criterion aimed at addressing higher seasonal inflow pulses which have apparent ecological significance may be ascribed a timing and volume based on other more "mechanistic" information such as productivity-inflow relations or peak abundance characteristics of key species.

In the third step of the inflow pattern approach, the target for future occurrence for each criterion must be chosen. A typical approach would be to determine the attributes, such as volume, frequency and duration, under historical or natural conditions and then, using a combination of scientific evidence and professional judgment, determine an allowable departure that will still maintain the intended ecosystem function.

### 4.3.2.2 Strengths and Weaknesses

Strengths of inflow pattern approach include:

- Method focuses on maintaining characteristics of the estuary natural inflow regime.
- Can accommodate several criteria, each based on an ecologically-relevant inflow pattern.
- Criteria can be based on variety of inflow metrics. Examples include: inflow percentiles from historical or natural record, inflows to maintain a target salinity; inflows linked to productivity levels of select species or communities.

Weaknesses of inflow pattern approach include:

- Requires specification of inflow patterns with apparent important roles in the estuary. May be hindered by lack of data or inability to link ecosystem functions to inflow.
- Requires specification of an acceptable change in key inflow events as measured by one or more of the attributes: volume, timing, frequency, duration.

### 4.3.3 Percent of Flow Approach

The percent of flow approach was developed in Florida. Florida defines the need for inflows broadly as "the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area." Florida is divided into five Water Management Districts, which were established in 1972. The result is that freshwater inflow studies and rules are unique to each estuary, and the different Florida water management districts have adopted different strategies for regulating freshwater flows in response to different intensities of human engineering and societal expectations of water management (e.g. flood control versus water supply). For example, for the rivers and streams draining into Tampa Bay, the withdrawal is limited to a percent of streamflow at the time of withdrawal (Flannery et al. 2002).

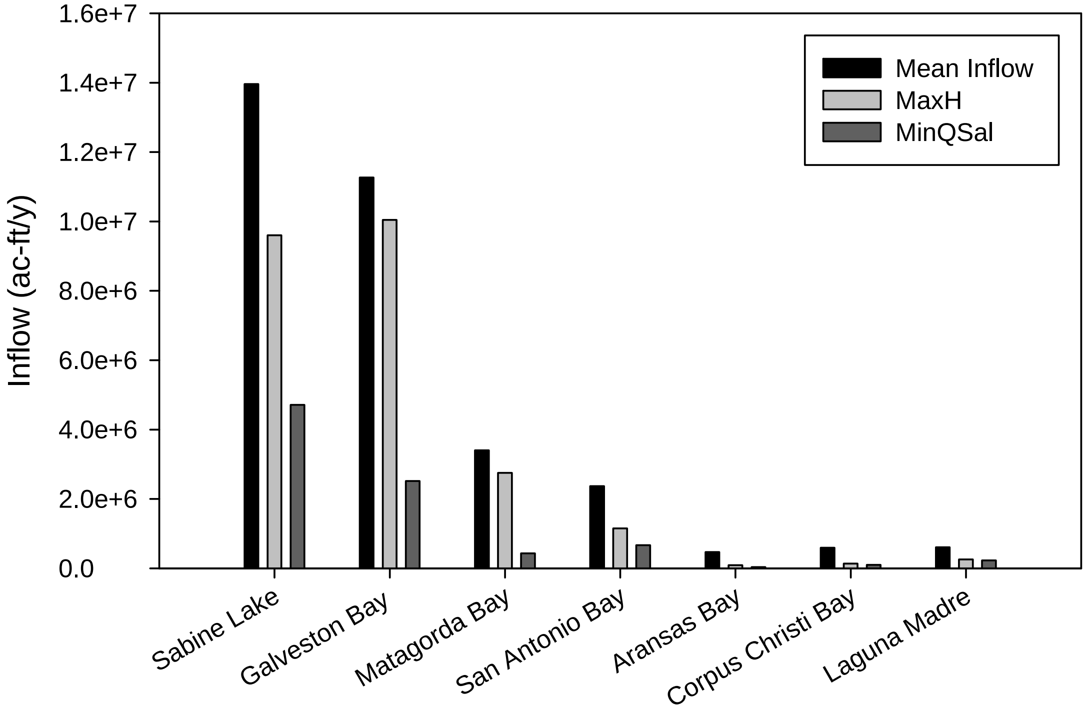
The percent of flow approach is similar to the hydrological approach. In Florida, the approach is based on the assumption that the natural flow regime is considered the baseline for assessing effects of withdrawal. Because the biological response to altered flow is often nonlinear, the environment is protected during low inflow periods by taking a small percent of the volume. Although the rule is based on percent of flow, identifying the value follows a familiar course of action: first key species are identified, then regressions are performed between species abundance and flow rates to determine the natural range, then a percent reduction value is chosen. The choice depends on expert opinion and can be arbitrary.

There is no reason to think that there is one magic number or that any given methodology would lead to similar percent flow values in different ecosystems. For example, the TxEMP solutions using the State Methodology (Table A-4) yield a variety of different percent flow solutions (Figure 4.3-4). The flow recommendations range from 10% of annual flow for *MinQSal* in Aransas Bay to 90% for *MaxH* in Galveston Bay.

#### 4.3.3.1 Strengths and Weaknesses

Strengths of percent of flow approach include:

- It is quick and simple because the flow data are readily available on the TWDB website and the statistical summary calculations are routine.
- It is intuitive that the change in the environment is proportional to inflow reductions.
- Choosing a percent number is a democratic governance process that relies on best expert opinion, collaboration, cooperation, and negotiation among stakeholders.



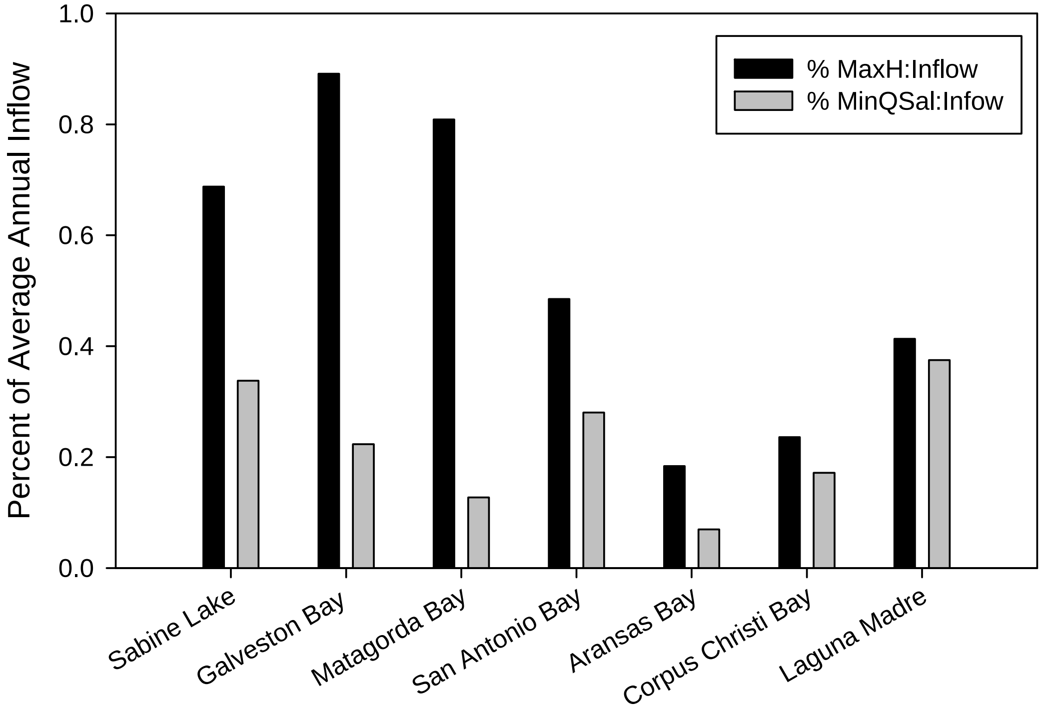


**Figure 4.3-4 Inflow Solutions Using TxEMP (Table A-4) Relative to Average Annual Inflow Volumes (top) and as a Percent of Flow (bottom)**

- It shares characteristics of the hydrology-based approach, but the human decisions are more transparent in the outcome, because the number comes through stakeholder deliberation, not a model.
- It is easy to create a metric (e.g., salinity or a population abundance) to monitor and use in an adaptive management process.
- Outcome provides a regime in that natural conditions are simply proportionally reduced.
- Allows more water to be diverted during floods if the percent values vary with flow rates.

Weaknesses of the percent of flow approach include:

- It is easy to pick a percent number that is arbitrary.
- The relationships between flow, environmental condition, and biotic responses are not linear. Yet, the assumption of linearity is fundamental to the percent of flow approach. Since the reduction of flow is arbitrary, it may in fact have an excessive impact on the estuary, or it may limit diversions from the rivers when such diversions might be ecologically acceptable.
- It is an empirical approach based on hydrological data (but some argue this is actually a strength).
- It completely avoids the question of the quantitative impact of flow reduction on biology. Moreover, even though the effect of such a reduction may be "monitored", it's not apparent what actions might be taken if these impacts prove excessive.

## 4.4 OTHER CANDIDATE METHODS

While the emphasis in this section is on methods that have some record of application or relevance to the bays and estuaries of Texas, there are several recent approaches that warrant mention, and are briefly summarized here.

### 4.4.1 Nature Conservancy (IHA/EFC) Method

The Index of Hydrologic Alteration (IHA) method was proposed by Richter et al. (1996), staff members of The Nature Conservancy (TNC) and its contractors, and is the basis for a software product, the IHA Program. The purpose of the IHA method is to quantify the alterations in the stream regime, generally but not necessarily resulting from human activities, especially for use in appraising predicted modifications due to proposed projects. Changes in the numerical values of the indices are proposed as a metric for evaluating the resulting impact to the hydrological regime, hence to the stream ecosystem. The IHA indices are more useful as an impact evaluator than a means for estimating environmental flows.

In its latest version (TNC, 2007), the IHA software product includes an evaluation of "Environmental Flows Components (EFC)". The evolution of this capability of the IHA is summarized by Mathews and Richter (2007). The fundamental tenet of the method is that the stream ecosystem is dependent upon a "regime," by which is meant a suite of statistics that quantify components of variability in streamflow, the occurrence of many of which is seasonal. The EFC part of the program works with a record of daily flows and first sorts these data into categories, which we refer to here as "pulse" and "non-pulse" (to avoid the confusing terminology of TNC). The sorted data record is then used to compute statistics of five categories of flow or flow event, listed below. :

| | |
|---|---|
| Large floods (event) | Large, rare pulse events (return interval greater than 10 years) |
| Small floods (event) | Infrequent, moderate pulse events |
| High-flow pulses (event) | Frequent pulse events (return interval < 2 years) |
| Low flows | monthly central value of flows exceeding the lowest decile non-pulse flows |
| Extreme low-flow (event) | time series of flows that never exceed the lowest decile non-pulse flows |

The procedure for "parsing" the daily flow time series into these five classifications is depicted in Figure 4.4-1. In both the figure and the listing above, it is emphasized that four categories of hydrological "events" are separated in the daily-flow time series, *viz*. three "flood" events, and the "extreme low-flow" event. The remainder of the daily-flow data is categorized as "low flow" and monthly central measures (i.e., means or medians) are computed to characterize the annual pattern of flows. The events are parameterized by intensity, duration and date of initiation, and, in the case of the flood events, probability of occurrence (as measured by a return interval).

The IHA Program has become increasingly popular as a means of quantifying environmental flow components, especially when stream condition and biological data are lacking. In particular, it is one of the options available in the HEFR method (see Section 4.3.1 above, and citations therein).

While no instance could be found in which this EFC method has been applied to a large lagoonal estuary typical of the Texas bays, in principle this could be carried out (cf. Appendix B). The only requirement is that the total inflow to the estuary has to be specified as a daily time series. Certainly, the gauged components of the inflowing rivers are compiled as daily time series (see Section 3.1), and for many of the estuaries daily TxRR output is available back to the late 1970's. The advantages attending such an application would be that it is straightforward, exploits software that is freely distributed, well-supported and has modest platform requirements, and would represent a generalization of a procedure that has already engendered considerable employment in the riverine environment. The chief disadvantages are (1) the mechanisms invoked to justify the ecological significance of the environmental flow components in a riverine setting do not readily translate into the estuarine environment, (2) because of the long integration of the inflow signal in the responses of the estuary, it is not at all clear that the same process of identification of the flow events is meaningful, and (3) even if one can argue that the EFC "events" are ecologically significant to the estuary, the method does not quantify a relation between these events and some measure of ecological productivity.

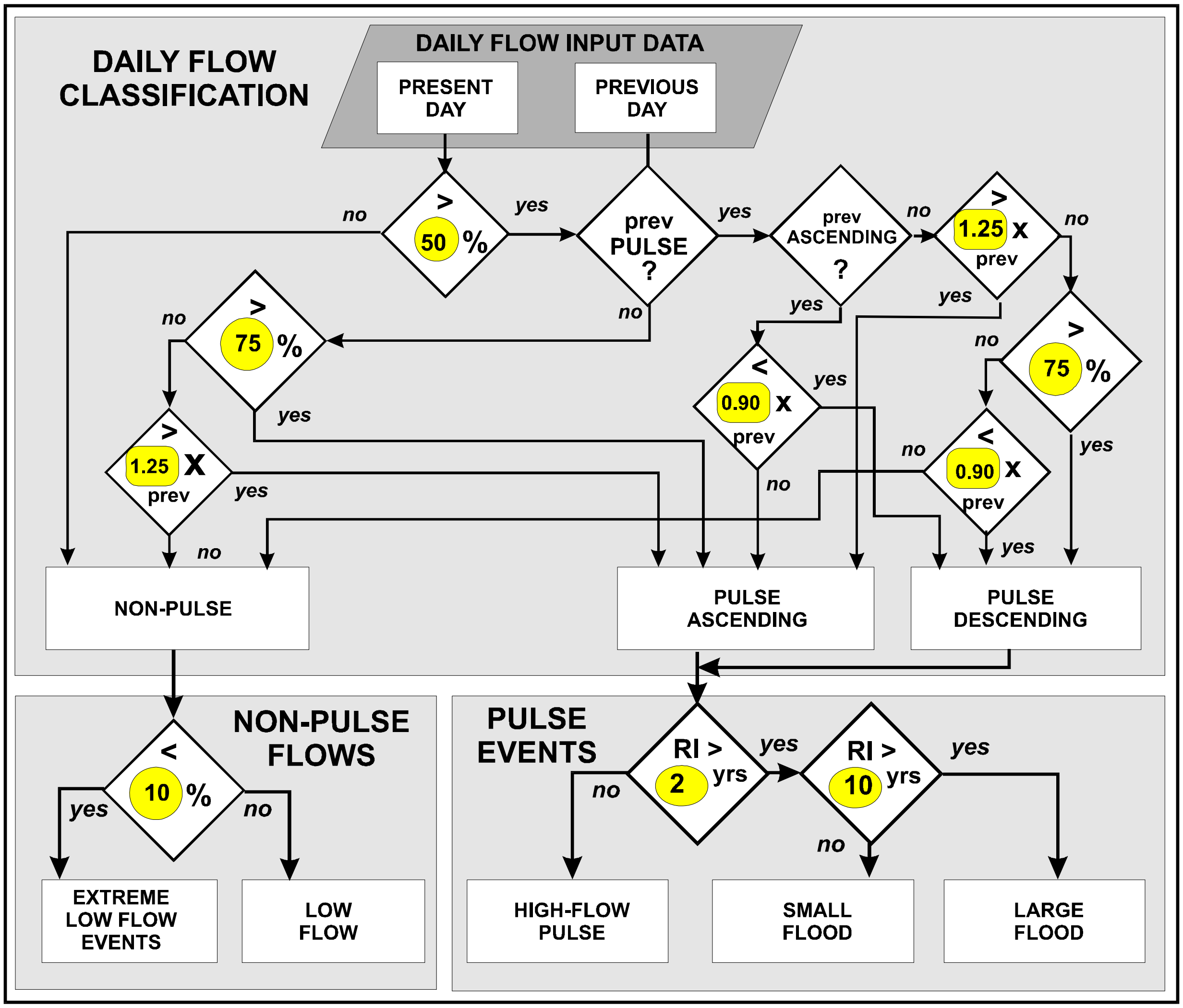


**Figure 4.4-1 Flow Diagram Illustrating the Processing Strategy for Separating Flow Record into Environmental Flow Components**

### 4.4.2 LCRA-SAWS Inflow Criteria Method

To support the proposed LCRA-SAWS Water Project (LSWP), studies of Matagorda Bay (often referred to as the Matagorda Bay Health Evaluation (MBHE)) entailed development of substantial modeling and data analysis, which was employed to assess the relationship between causative factors and resulting bay condition. Several measures of bay condition were investigated, including salinity, habitat condition, species abundance, nutrient supply, and benthic condition. These various models and data analyses were used to establish a suite of recommended Matagorda Bay Inflow Criteria for the Colorado River, which, if achieved in the future, should be protective of bay health and productivity. The full development of the inflow criteria is reported in MBHE 2008.

The principle MBHE models employed to develop the criteria are the salinity, habitat, oyster, and benthic modeling for most inflow levels, and the nutrient modeling and data analyses for the long-term flow component. While extensive biostatistical analyses relating species abundance to freshwater inflow was conducted as part of the MBHE, these results were not used directly in the development of inflow criteria. These analyses were useful in testing the inflow recommendations against historical biological data, and confirmed that the recommendations fell within the bounds of previously observed data.

An initial objective was that the inflow criteria needed to be comprehensive and cover the full flow spectrum from very low flows (near drought-of-record conditions), in which species refuge becomes of primary importance, to higher flow events sufficient to provide adequate nutrient supply to the bay system. The MBHE freshwater inflow categories and specific criteria, as summarized in Table 4.4-1, include a wide range of inflow conditions with the goal of providing the essential components to maintain the health and productivity of Matagorda Bay.

The techniques to develop specific components of the inflow criteria suite focused on appropriate "Design Areas" where different MBHE modeling and data analysis tools were applied (see Figure 4.4-2). These areas ranged from the substantial and important Delta area being formed at the mouth of the Colorado diversion channel, which was used to assess very low flow conditions, to the upper half of the Eastern Arm of Matagorda Bay (EAMB) for the inflow regime portion, and finally, to the entire EAMB for higher flow conditions. In essence, these design areas represent appropriate geographic areas in the bay in which desired conditions (often expressed as salinity ranges) can be related to inflow from the Colorado River using the MBHE models.

**Table 4.4-1 MBHE Freshwater Inflow Categories and Specific Criteria**

| Inflow Category | Inflow Criteria | Description |
|---|---|---|
| LONG-TERM | Long-term Average Volume and Variability | provide adequate bay food supply to maintain the essential food supply and existing primary productivity of the bay system |
| MBHE INFLOW REGIME | MBHE 4 | provide inflow variability and support high levels of primarily productivity, and high quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat. |
| | MBHE 3 | provide inflow variability and support quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat. |
| | MBHE 2 | provide inflow variability and sustain oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat |
| | MBHE 1 | maintain tolerable oyster reef health, benthic character, and habitat conditions |
| MINIMUM | Threshold | refuge conditions for all species and habitats |

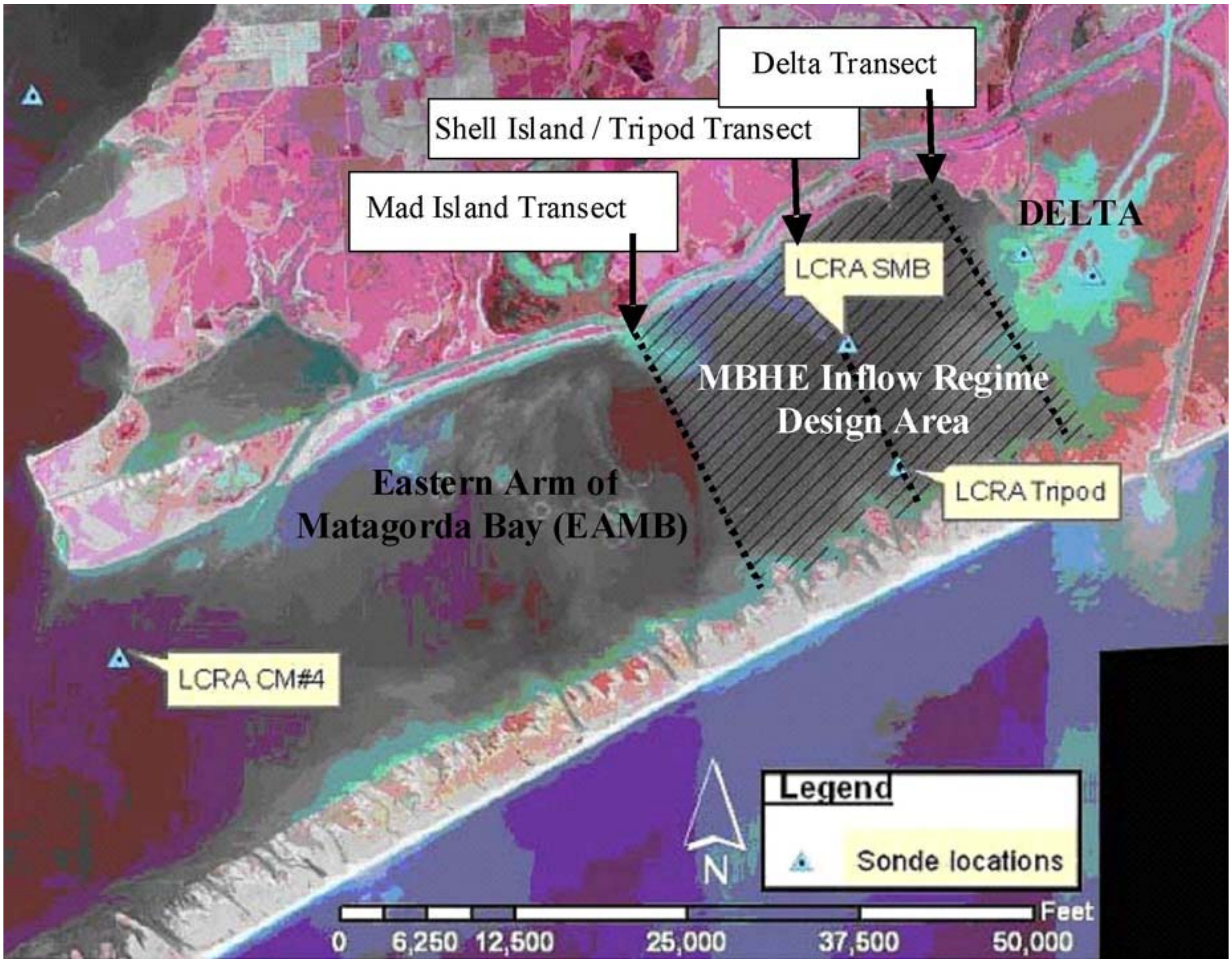


**Figure 4.4-2 Design Areas Used in LSWP Matagorda Bay Health Evaluation**

Habitat modeling was utilized to provide relationships between the Weighted Useable Area for several key species and salinity as reported in MBHE 2007. Oyster and Dermo modeling, also described in this report, was utilized particularly in the development of low flow recommendations. Nutrient modeling was also performed using the EPA WASP model to determine the relationship between freshwater inflow, nutrient loading, and primary productivity, as measured by chlorophyll-*a*. Finally, salinity condition related to benthic populations was also investigated to set salinity targets for each of the inflow criteria level. The levels in the inflow criteria suite can be described as follows:

> **Long-term Average Volume and Variability Criteria.** An essential element of the criteria is the need to maintain the flow amounts and patterns that provide a major source of food to support the health and productivity of the estuary and maintain phytoplankton primary production. An important and widely used measure of this primary production is the concentration of phytoplankton chlorophyll-*a* in the water column. Both field data and modeling have confirmed a functional relation between the concentration of chlorophyll-*a* in the EAMB and the amount of inorganic N carried by river inflows. Inflows carrying inorganic N as well as organic matter are important drivers of the ambient level of

chlorophyll-*a* and primary productivity in the EAMB, particularly under higher flow conditions, since a large portion of the nitrogen and organic matter loads are conveyed to the EAMB during higher flow events. Maintaining these flow pulses, an important part of the variability, is thus essential to meeting the historical long-term average level of primary productivity.

**MBHE Inflow Regime Criteria.** The MBHE 1-4 criteria involve an inflow regime aimed at maintaining the health and productivity of Matagorda Bay.

> **MBHE 4** criteria are recommended to bridge the gap between long-term volume and variability and MBHE 3. MBHE 4 criteria allow for a high level of primary productivity and when implemented in concert with the other MBHE criteria, enhance the intra-annual variability so valuable to estuarine systems. MBHE 4 criteria would likely take place during average climatic conditions. The reference to climatic conditions just represents conditions that would likely cause salinity ranges associated with these criteria, not operational triggers. The goal for the MBHE 4 criteria is to maintain high quality conditions for oyster health, benthic habitat, low estuarine marsh, and shellfish and forage fish habitat throughout the entire upper EAMB Design Area. This in turn will provide near optimal conditions for all trophic levels within the delta. This spatial expansion of high quality habitat and added inflow variability to the system will assist in maintaining the health and productivity of Matagorda Bay.
>
> **MBHE 3** is recommended to support intra-annual variation in the inflow regime. MBHE 3 criteria would likely take place during somewhat below average climatic conditions with the reference to climatic conditions representing conditions that would likely cause salinity ranges associated with these criteria, not operational triggers. The goal for MBHE 3 is to maintain higher quality conditions for oyster health, benthic habitat, low estuarine marsh, and shellfish and forage fish habitat than the lower two MBHE criteria. This spatial expansion of higher quality habitat and added inflow variability to the system will strengthen the MBHE inflow regime.
>
> **MBHE 2** is also recommended to provide intra-annual variation and would likely take place during dry but not extreme climate conditions. Again, this just represents conditions that would likely cause salinity ranges associated with this criteria, not operational triggers. The goal for MBHE 2 is to sustain conditions of oyster health, benthic condition, marsh productivity, and shellfish and forage fish habitat. During these relatively dry conditions, the mid-bay region would experience lower quality ecological conditions for each trophic level. Depending on inflows from the Lavaca Basin, it is also likely that during these conditions the reefs, benthic habitat, low estuarine marsh, and shellfish and forage fish habitat would be largely reduced further west into the Matagorda Bay system. These low inflow and higher salinity conditions have been experienced in the past and will no doubt be experienced in the future, and, as previously noted, play an important ecological role in an estuary.
>
> **MBHE 1** embodies salinity conditions that would naturally be experienced during fairly extended dry conditions, though less extreme than those experienced at the Minimum

inflow category. These climatic conditions are descriptive of what it would likely take to cause the salinity ranges associated with this criteria, but do not imply operational triggers. Although the role of low flows may not always appear as beneficial based on modeling results, they do support the long-term variability to which native species have evolved. Important roles include marsh die-off, promoting native species, and promoting genetic strengthening. Marsh die-off provides organic matter input not only for nourishment of the soils for continued marsh development but also as a source of bay food. Higher salinities and other water quality parameters are extreme conditions that are observed naturally. Experiencing these natural extremes puts stress on non-native species and promotes the survival of the fittest concept within the native flora and faunal community. As discussed for the Threshold criteria below, extended low-flow periods also have negative effects that may alter the character of the bay if experienced outside the realm of historical conditions.

**Threshold Criteria.** Extremely low freshwater inflow conditions (i.e., at or near drought of record) do occur in natural systems. An estuary is different than a river in that a bay will not go dry with no inflow. This condition allows some level of habitat to remain, but it worsens as the bay gets saltier, warmer, has less food supply, etc. Short periods of such extreme conditions can provide benefits that include marsh die-off (source of organic matter input to the bay) and genetic strengthening (survival of the fittest). However, continued conditions can lead to excessive marsh die-off which can destabilize marsh sediments leading to erosion and overall marsh loss. Positives and negatives relative to an estuarine inflow regime are the foundation for ecological variability and the long-term health of an estuary. It is the frequency and duration of these extremely low to no inflow periods that, if extended beyond the natural tendency of the bay, can shift the ecological community to a more saline tolerant assemblage (e.g., Laguna Madre). While the Laguna Madre is considered a healthy and productive system, its condition would likely not meet the test of "maintaining the health and productivity of Matagorda Bay."

The MBHE Regime and Threshold criteria largely utilize salinity ranges as the surrogate for determining if desired habitat conditions are being achieved. Hence salinity becomes the link between freshwater inflow and biological result. In the LCRA-SAWS studies, relating bay salinity conditions to freshwater inflow was accomplished using a hydrodynamic/salinity transport model based on the U. S. Army Corps of Engineers RMA-2 and RMA-4 code. To provide a long-term simulation of bay hydrodynamics and salinity, the required input data was assembled to model the period from July 1995 through December 2003. This span of time included two extended low flow periods of 20 and 22 months, respectively, as well as a 22-month period of high flow. These results provided the underlying hydrodynamics and salinities for the habitat and nutrient modeling, as well as flow/salinity relationships. Using the long-term model output, regression equations were developed (see Figure 4.4-3) relating salinity conditions at various transects within the upper EAMB design area with flow in the lower Colorado River. In this manner, flow levels resulting in desired salinity conditions can be estimated.

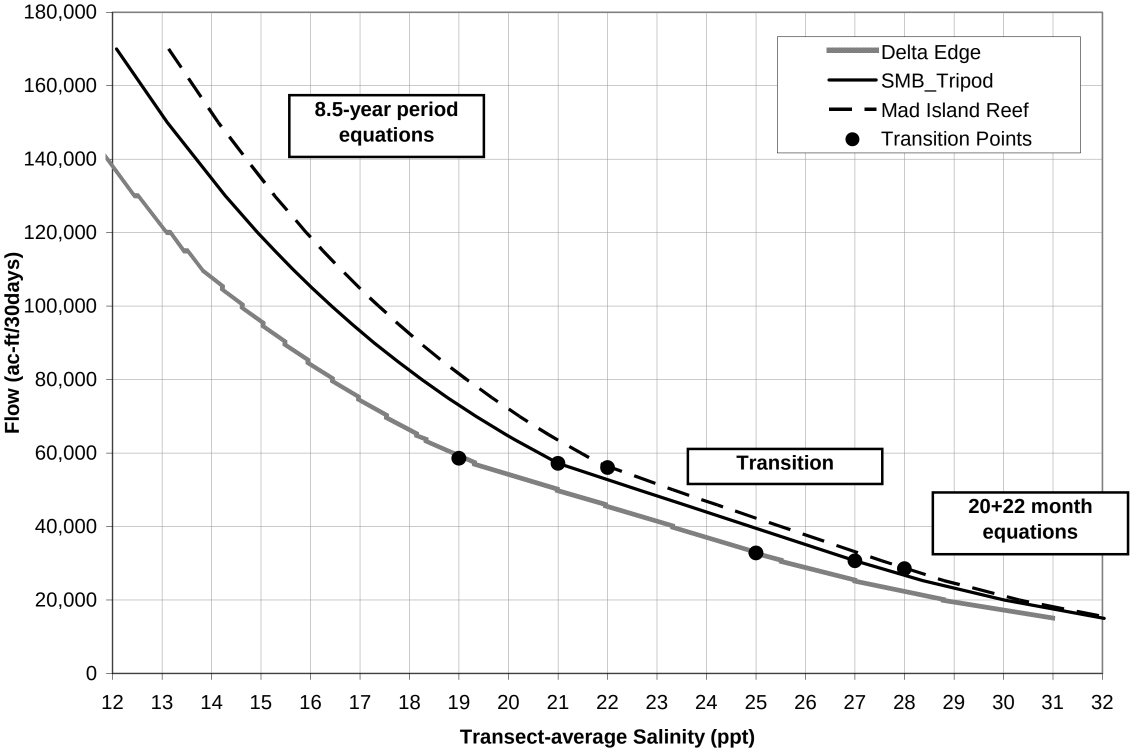


**Figure 4.4-3 Salinity-Colorado River Inflow Regressions**

The timing of freshwater inflow to a bay has long been acknowledged as being extremely important in maintaining the ecological productivity of the system. For ease of planning and perceived operational constraints, flow recommendation methods often adhered to a fixed calendar (e.g. monthly, quarterly, etc.). However, estuarine organisms react less to specific calendar months, but rather are considered to be responsive to pulses of nutrients, alterations in salinity, and the suitability of habitat conditions, along with many other factors, throughout their respective life cycles. In the MBHE studies, this motivated the formalization of a hydrological seasonal pulse or "freshet" and its incorporation into the inflow criteria developed for Matagorda Bay. The freshet methodology employed is more fully described in MBHE 2006. The results of the seasonal analysis was to establish a three-month "spring" pulse volume which could occur any time during the January through July period, a three-month "fall" volume between August and December, and an "intervening" volume to occur over the remaining six months, wherever they occurred. Hence, the actual numerical criteria for each of the MBHE Inflow Regime level are a set of three volumes distributed seasonally.

The final aspect of the MBHE proposed criteria is a set of achievement guidelines, expressed as desired occurrence frequencies, for each of the inflow criteria levels. For the recommended Threshold criteria, and the Long-term Volume and Variability criteria, the MBHE studies recommended a 100% achievement guideline. For the four MBHE Regime criteria, recommended frequency of occurrence were based on statistical analyses of both historical flow and salinity data, as more fully described in MBHE 2008.

Because the proposed criteria embody recommended achievement guidelines, which suggest that certain flow conditions should be maintained or exceeded a certain percentage of the time, it is necessary to utilize a forecast of future inflow conditions to determine if the criteria will be satisfied. In the LCRA-SAWS studies this was accomplished using a WAM-type model developed for the Colorado Basin. In the case of the lower Colorado, operationalizing the proposed criteria requires establishment of an operating protocol for the Colorado River system that, when superimposed on historical hydrology, yields results satisfying the full suite of inflow criteria. The MBHE team also suggested that the operations process could provide an opportunity to adjust the operating protocol when unusual conditions in the coastal inflows (substantially higher or lower than normal) exist. Adopting this type of adaptive management would provide an opportunity to both protect bay health and productivity and meet long-term water supply needs.

# SECTION 5
# OTHER CONSIDERATIONS

In previous sections, the focus has been on identifying the hydrology of inflow as it alters salinity habitat conditions, and how those conditions might affect biological resources. However, there are other important considerations such as: 1) estuary conditions today are a function of historical and ongoing changes, 2) inflows provide the bulk of the sediment needed to maintain shoreline habitats, and 3) inflows provide much of the nutrient supplies to the estuaries.

A sound ecological environment typically includes having inflows maintained at appropriate levels and with general temporal patterns that are supportive of existing habitats. However, it also requires that the key constituents of water quality and productivity be supplied with reasonable continuity as well. Some of the key constituents include sediments, organic matter, and nitrogen, which is the nutrient most likely to be limiting to primary productivity in Gulf Coast estuaries. The biological responses to nutrients, organic matter and sediment flowing into the bays and estuaries occur in the context of the historical changes that have taken place along the coast as human populations have increased.

As noted in Section 2, while the ideal model of the estuarine ecosystem would encompass simultaneous solutions to all the applicable relations delineating all the key variables, the fact is that this may not be feasible because: 1) the relevant variables may exert different levels of control over the ecosystem, and, therefore, vary in relative importance in different places, 2) the scientific basis for causal relationships expressed via a mathematical model may be unequal, and therefore the associated uncertainty will vary, and 3) the connections to freshwater inflow may diverge among the controlling variables. Given this complex situation, it is useful to focus a large portion of the quantitative efforts on inflow (and that is the approach taken by Senate Bill 3), specifically the effects of inflow on organism abundance, as manifested either by a direct relationship or through the intermediate variable of salinity. Nevertheless, other variables can exert a real effect on the relation between inflow and the estuarine ecosystem and should not be ignored. This modifying role of additional variables is referred to as an "overlay" for purposes of this report. In the case of Figure 2.1-2, the relationship between inflow → salinity → biology, salinity is considered the primary variable because it is related to inflow (albeit with uncertainty), and most estuarine organisms are affected by salinity, a key measure of the chemical habitat. A direct relationship between inflow and biology could supplant an indirect relation through salinity, if the data are adequate and the relation well established. The variables of nutrients and sediment, in the context of historical changes, have important but complex roles in coastal ecosystems, but the existing data base is frequently inadequate for developing statistically valid quantitative relationships that can be effectively applied in a predictive fashion. Therefore, they are addressed here as "overlays," to be employed to modify or supplement the inflow regime specifications.

## 5.1 HISTORICAL CHANGES

It should be recognized that all Texas bays that we know today have been modified substantially from their historical, natural condition due to agricultural practices, fishery harvests, navigation channels, inflow pattern modifications, waste discharges, and other factors. Approximately 80% of marine pollution stems from land-based sources, so estuaries are the most susceptible to pollution effects, especially those adjacent to urban areas (Kennish 1998). Considering the length and large size of the Texas coast, there are relatively low human population sizes near the coast. Houston (about 2.2 million people in the city and 5.6 million in the metropolitan area) is the only very large city in Texas within 50 miles of the Gulf of Mexico, and Corpus Christi (about 286,000 people in the city and 414,000 in the area) and Beaumont-Port Arthur-Orange (with a combined population of about 400,000) are the only medium size cities directly on a bay. Consequently, when national assessments are performed, Texas estuaries are judged as being in relatively good condition, except for a few localized industrialized sites. For example, Texas mollusks and fish had among the lowest tissue contaminant values found during the NOAA Mussel Watch and Status and Trends national programs (Mearns et al. 1988, NOAA 1995, O'Connor 1994). Also, the recent NOAA national eutrophication survey found that the overall eutrophication condition along the Texas coast was low-moderate to moderate (Bricker et al. 2007).

Specifying an inflow regime which maintains a sound ecological environment is the key requirement for environmental flow recommendations under Senate Bill 3. A reasonable management goal is to maintain the modified, but still sound ecological environment that has evolved for each bay system, and this requires consideration of multiple sources and processes. These include:

- Changes in water exchange with the Gulf, as affected by deeper navigation channels, inlet modifications, and relative sea level rise,
- Changes in the level of commercial and recreational fishing pressure,
- Changes in the supply of sediment and nutrients resulting from water supply and flood control projects in each watershed,
- Changes in inputs from rain and wastewater discharges that can affect the magnitude and composition of nutrient inputs, and
- Changes in the amount and quality of tributary inflows resulting from land use changes and agricultural practices.

All of these changes to the watersheds and bays have been important over the last century, and these aspects are continuing to change, in some cases at an accelerating rate.

The bays and estuaries of Texas are changing still. Certainly population growth and consequent urbanization will continue. Climate change is increasingly of concern and could be especially important on the Texas coast because its flat terrain makes it susceptible to sea level rise (Montagna, et al, 2007; Montagna, et al, 2009). Sea-surface temperature change and changes in weather patterns will also affect the Texas coast. While it is likely that climate change is mainly a concern for the future, the basis for a recommended inflow regime should include cognizance that historical patterns may change, or already may be changing.

## 5.2 SEDIMENT AND NUTRIENT LOADINGS

With future regulatory analyses of both inflows and constituent inputs, decisions will be required on how much of a change from current conditions is acceptable. Those decisions will be informed by knowledge of both the current condition and the longer-term pattern of evolving changes. For this reason the recommended approach to addressing sediment inputs and nutrient loadings is to perform both:

- A present-conditions quantification in the form of a sediment, nutrient, and organic matter budget, and
- Development of a long-term analysis of the changes or trends in key parts of the budget.

The present sediment, nutrient and organic matter budget should reflect current conditions in an average year as well as representative wet and dry years. The long-term budget should address the changes that have occurred over the last century in direct inputs, land use in the watershed, and bay physical and water exchange conditions, to the extent practical. Ideally this would include considering the effects of changes in the chemical form and ratios between the key nutrients.

### 5.2.1 Sediment Delivery to Bays and Estuaries

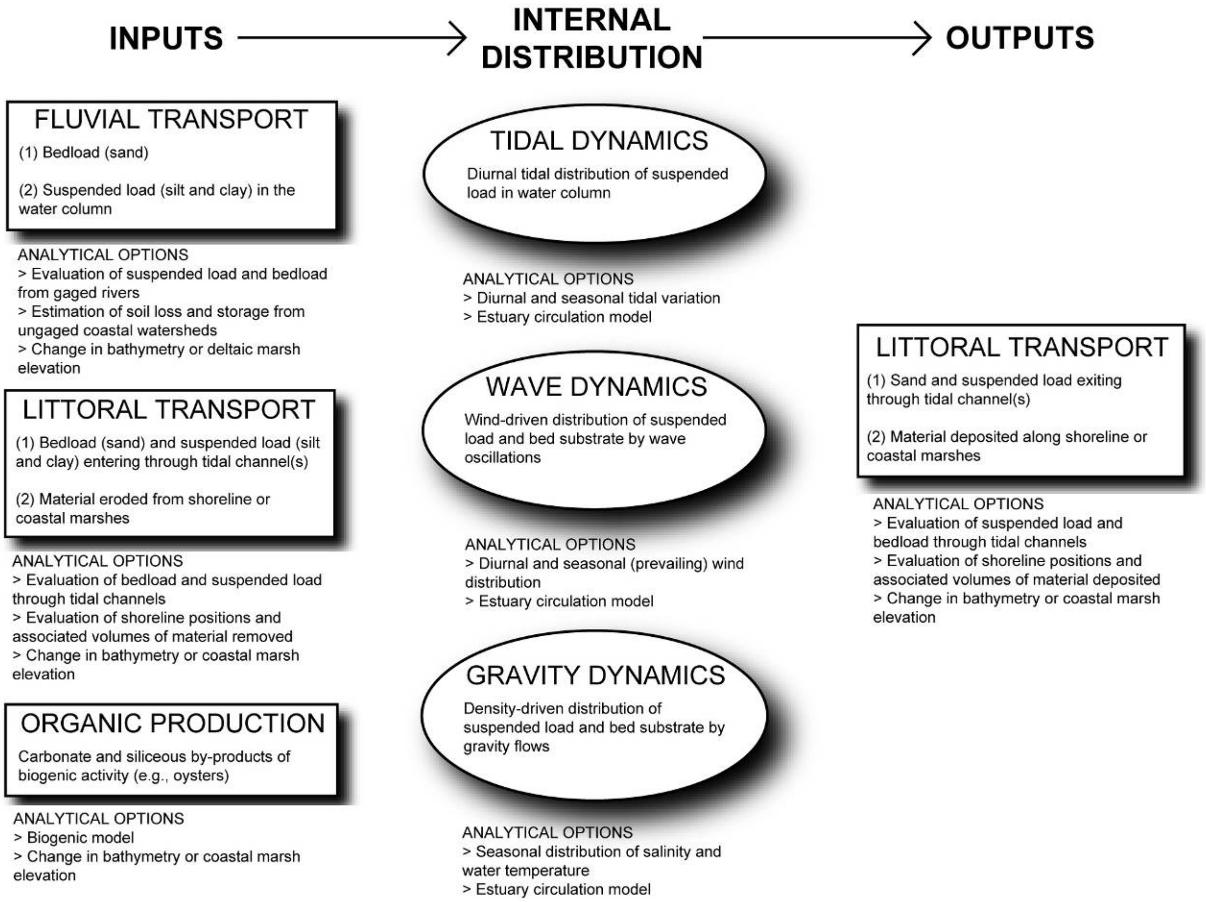
Bays and estuaries are dynamic transitional systems that absorb inputs and disturbances from both rivers and oceans, including inland floods and coastal storms. Over the course of hundreds to thousands of years, their physical dimensions adjust with sea-level fluctuation, ground-surface subsidence, sediment delivery rates, and organic production rates (e.g., oyster beds). In historical times, especially in the case of the Texas bays, they have been greatly modified by channelization, among other direct and indirect anthropogenic actions. It is imperative, therefore, that in evaluating ecological conditions one recognize that significant anthropogenic changes have been made, and that it may not be possible to revert to previous unaltered conditions. Notwithstanding, sediment delivery is one of the natural processes that should be considered for maintaining the ecological integrity of bays and estuaries.

The transport of sediment from watersheds draining to bays and estuaries is a vital process that maintains deltaic and coastal marsh environments, minimizes shoreline erosion, contributes to benthic habitat composition, and affects turbidity in open-water environments (Ward and Montague, 1996). As much as bays and estuaries represent a transition from fresh- to saline-aquatic conditions, they also represent a shift from fluvial- to coastal-dominated sediment transport processes. During normal hydrologic and tidal conditions, suspended sediment can remain in the water column, be deposited in low-elevation coastal margins, or settle to the bottom in low-energy estuarine settings. In addition to these processes, floods or abnormally-high tides can result in the deposition of suspended sediment in deltaic marsh environments or relatively high-elevation coastal wetlands. Coarser sand-sized sediment supplied by bedload-transport processes contributes to deltaic progradation, forms a considerable portion of benthic substrate, and comprises the majority of sediment reworked by coastal processes along shorelines and beaches. Various characteristics and processes associated with estuarine sediment are described in Ward and Montague (1996).

Healthy and sustainable bays, estuaries, and coastal environments require a sufficient sediment supply from rivers and streams. Threats to sediment supply include upstream reservoir impoundments, sand and gravel extraction activities, certain flood mitigation efforts, and various land-use practices. Upstream threats to sediment supply are compounded by various coastal processes that counteract sediment inputs, including sea-level rise, ground-surface subsidence, and storm erosion. Approaches that account for sediment delivery into bays and estuaries should consider the volume for a given timeframe, thereby informing an assessment of the sediment budget (Figure 5.1-1). Sediment budget assessments are difficult for estuaries because of the complex exchanges between rivers and open-water environments (Wright and Schoellhamer 2005), and commonly rely on historical bathymetry and substrate composition (e.g., Hobbs et al. 1992). The most straightforward approach is using historical sediment-load data or sediment-load model equations at the downstream-most streamflow-gaging station of coastal-draining rivers and streams (e.g., Solis et al. 1994). This approach does not consider ungaged watersheds and, if measured or estimated for a degraded river, might not represent the natural conditions responsible for ecological integrity of the bay or estuary. For smaller, ungaged watersheds draining to bays or estuaries, a relatively simple approach to estimate sediment load could be application of a rainfall-runoff model coupled with a soil-loss equation (e.g., Revised Universal Soil-Loss Equation). Soil-loss equations, however, only predict the earth material removed by erosion and do not account for subsequent storage within the watershed, which would result in overestimates of loads delivered to estuarine systems.

An alternative approach to estimate the sediment required to sustain the physical dimensions of bays and estuaries is a static volumetric assessment of the sediment necessary to offset shoreline erosion and relative sea-level rise (i.e., sea-level rise and ground-surface subsidence). For a known rate of relative sea-level rise, the rate of sediment delivery required for preservation of bathymetry in open-water environments and elevation of all marsh and deltaic areas could be computed. The target volume could be based on estimates of contemporary (or desired) bathymetry, the extent of subaerial coastal/deltaic wetland environments, biological contributions (e.g., shell fragments), and flux of sediment exchanged to oceanic areas through tidal channels (see Ward and Montague, 1996) of a given bay or estuary. A clear disadvantage of this approach is its disregard for natural trajectories of regressive (i.e., shoreline retreat) or transgressive (i.e., shoreline extension) behavior through time in estuarine systems. Further, the practical application of this approach is questionable when considering the uncertainty associated with estimates of sediment volume and flux. Despite the disadvantages of this approach, it offers a conceptual framework to assess the balance of oppositional processes that contribute to change in the physical dimensions of bays, estuaries, and coastal wetland environments.

One example that could be categorized as a volumetric approach is discussed in Hobbs et al. (1992) for Chesapeake Bay (Figure 5.1-2). The authors primarily utilized historical bathymetric surveys to estimate volumetric change of sediment. The conversion to sediment mass was done using measurements of sediment type (i.e., particle size), assumptions of sediment density, and computations of porosity. Further, the volumes of sediment delivered by shoreline erosion, mass of suspended sediment, and mass of biogenic sediment were included from previously published works. In summary, the investigation of the sediment budget for Chesapeake Bay utilized desktop methods to evaluate and synthesize previously published data, and serves as an example to guide similar endeavors in other estuaries.



FLUVIAL TRANSPORT
(1) Bedload (sand)
(2) Suspended load (silt and clay) in the water column

ANALYTICAL OPTIONS
> Evaluation of suspended load and bedload from gaged rivers
> Estimation of soil loss and storage from ungaged coastal watersheds
> Change in bathymetry or deltaic marsh elevation

LITTORAL TRANSPORT
(1) Bedload (sand) and suspended load (silt and clay) entering through tidal channel(s)
(2) Material eroded from shoreline or coastal marshes

ANALYTICAL OPTIONS
> Evaluation of bedload and suspended load through tidal channels
> Evaluation of shoreline positions and associated volumes of material removed
> Change in bathymetry or coastal marsh elevation

ORGANIC PRODUCTION
Carbonate and siliceous by-products of biogenic activity (e.g., oysters)

ANALYTICAL OPTIONS
> Biogenic model
> Change in bathymetry or coastal marsh elevation

TIDAL DYNAMICS
Diurnal tidal distribution of suspended load in water column

ANALYTICAL OPTIONS
> Diurnal and seasonal tidal variation
> Estuary circulation model

WAVE DYNAMICS
Wind-driven distribution of suspended load and bed substrate by wave oscillations

ANALYTICAL OPTIONS
> Diurnal and seasonal (prevailing) wind distribution
> Estuary circulation model

GRAVITY DYNAMICS
Density-driven distribution of suspended load and bed substrate by gravity flows

ANALYTICAL OPTIONS
> Seasonal distribution of salinity and water temperature
> Estuary circulation model

LITTORAL TRANSPORT
(1) Sand and suspended load exiting through tidal channel(s)
(2) Material deposited along shoreline or coastal marshes

ANALYTICAL OPTIONS
> Evaluation of suspended load and bedload through tidal channels
> Evaluation of shoreline positions and associated volumes of material deposited
> Change in bathymetry or coastal marsh elevation

**Figure 5.2-1 Conceptual Approach to Assess the Sediment Budget of a Bay or Estuary**

(Inputs include fluvial sediment, sediment delivered from offshore sources, and organically-derived material. Internal mechanisms distribute sediment throughout the estuarine system. Finally, sediment can exit the estuarine system through tidal channels or by depositional mechanisms.)

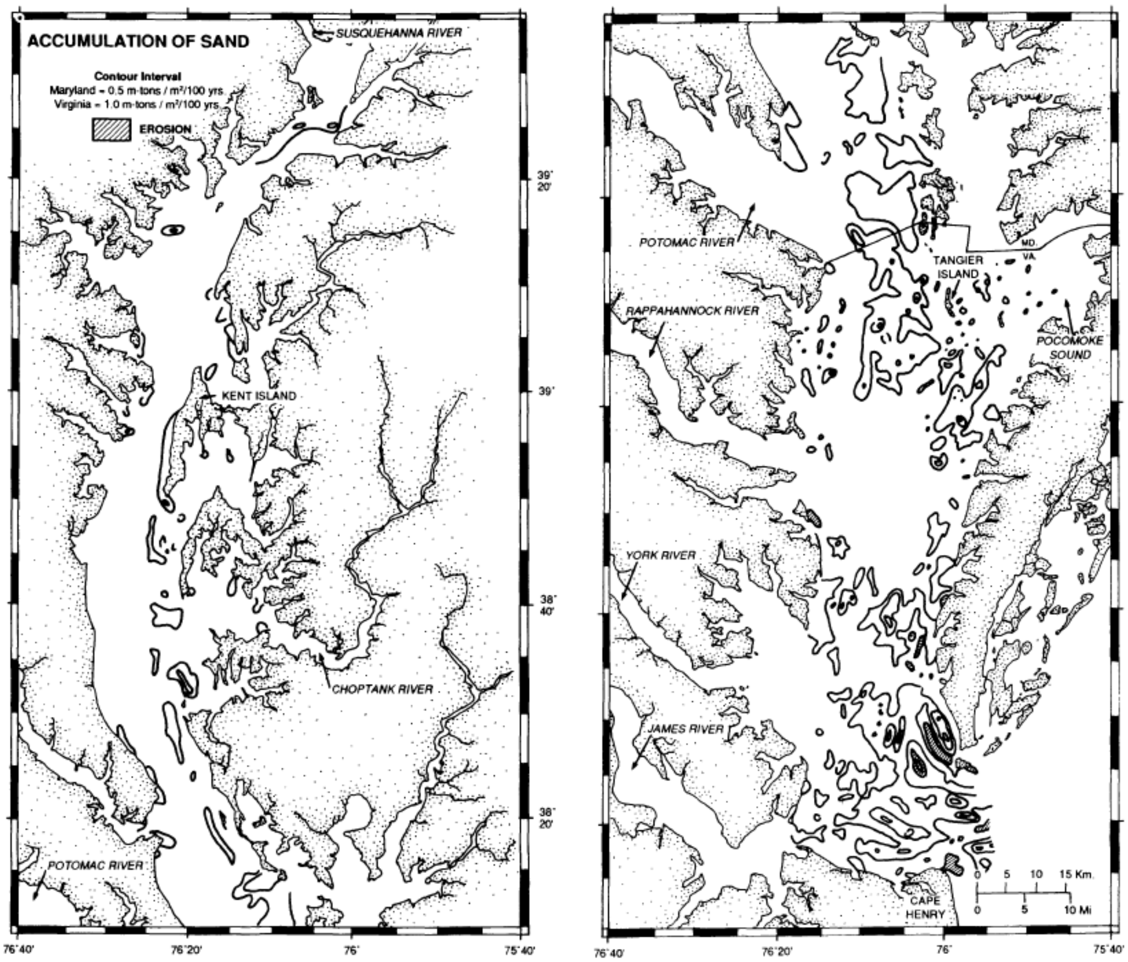


**Figure 5.2-2 Map of Sand Deposition Rates in Chesapeake Bay, USA**
(The data largely were derived from historical bathymetric surveys and previously published sources. )
Source: Hobbs et al. 1992

Although limited in ability to prescribe environmental flows, an estuary-circulation model (e.g., TxBLEND) adapted for sediment distribution could be informative in determining the fate of sediment in estuarine systems. A model that includes wind patterns, bathymetry, gravity currents, tidal fluctuations, and sediment loads and sizes might be able to predict locations and rates of sediment deposition in benthic zones, along the shoreline, and in tidally-influenced wetland environments. Although current models developed for Texas estuaries, including TxBLEND, are not specifically designed to address sediment dynamics, they could offer some information useful in predicting directions of sediment transport and locations of erosion or deposition. Development of new models or extensions of existing estuary-circulation models to include sediment dynamics would be a favorable research effort to inform inflow regime development programs in the future.

In summary, readily-available tools to assess the transport and distribution of sediment in bays and estuaries are limited. An elementary approach is consideration of sediment transport at the downstream-most gaging stations along coastal-draining rivers (e.g., SAC, 2009b). A more robust approach is an evaluation of the sediment budget, which estimates the inputs and outputs of sediment to an estuary. Sediment budgets commonly include historical bathymetric surveys, shoreline positions through time, and sediment transport estimates for rivers and tidal channels. A more advanced analysis of sediment distribution within an estuary would include circulation models of tidal-, wave-, and gravity-driven dynamics.

### 5.2.2 Nutrient and Organic Matter Delivery to Bays and Estuaries

Nutrient and organic matter delivery to the coast occurs nearly instantaneously when fresh water flows into bays (Shank et al. 2009). The rate of nutrient delivery is a function of inflow, which is pulsed during flood events. Nutrient delivery is coupled with sediment supply because nutrients are dissolved ions, and for some of them, their behavior is mediated by direct adsorption to silt. This is especially important for highly charged anions such as phosphate (Day et al. 1989). Both flocculation and adsorption are a function of salinity, and thus drive the concentrations of dissolved ions along the salinity gradient. Suspended silt, clay, and humic acids are negatively charged ions, thus ionic repulsion in fresh water dominates and stable suspensions are formed. This is destabilized as salinity changes in the estuarine gradient. Dissolved inorganic nitrogen is highly bioreactive. Typically, freshwater inflow introduces nitrates and nitrites, which are very quickly taken up by plants and microalgae as the water moves down the estuarine gradient. Thus, estuaries are sinks for these oxidized forms of inorganic nitrogen. In contrast, metabolism by all micro- and macro- organisms generates reduced forms of inorganic nitrogen such as ammonia. Because ammonification primarily occurs downstream in the more saline parts of the estuarine gradient, estuaries can be sources of nitrogen. Thus, the chemistry of an estuary resembles a mixing bowl where the mixing drivers that control concentration are the salinity gradient, suspended sediments, and biological metabolic processes.

The changes in water quality that are related to inflow are easily visualized using multivariate analysis. For Lavaca and Matagorda Bays, principal components analysis was used on a long-term water quality data set (Figure 5.1-3, top, Pollack et al. 2009). The first axis clearly represents an inflow effect, where a decrease in salinity (or increase in freshwater inflow) is associated with an increase in nutrients. The second axis represents a seasonal effect, with high temperatures correlated with low dissolved oxygen. Although freshwater inflow was highest in spring and fall, the variability was high enough such that inflow effects and seasonal effects were independent of one another. The importance of salinity zones defining habitat is described in Section 2.3. Station scores for each sample of the data matrix can be visualized on the same axes, and this indicates the salinity zones in the ecosystem (Figure 5.1-3, bottom). Thus multivariate analysis of existing datasets allows for distinguishing freshwater inflow effects from seasonal effects. In addition, salinity effects zones can be identified.

To assess environmental flow recommendations it is necessary to understand both current nutrient conditions and recent historical changes of nutrient supplies to bays and estuaries. Both will require some level of analytical effort.

Examples of present condition budgets for nitrogen (N) and organic matter are shown in the Tables 5.1-1 and 5.1-2 respectively, which are taken from work on the Matagorda Bay for the LCRA-SAWS Water Project (MBHE, 2005). These show the distribution of inputs by tributary

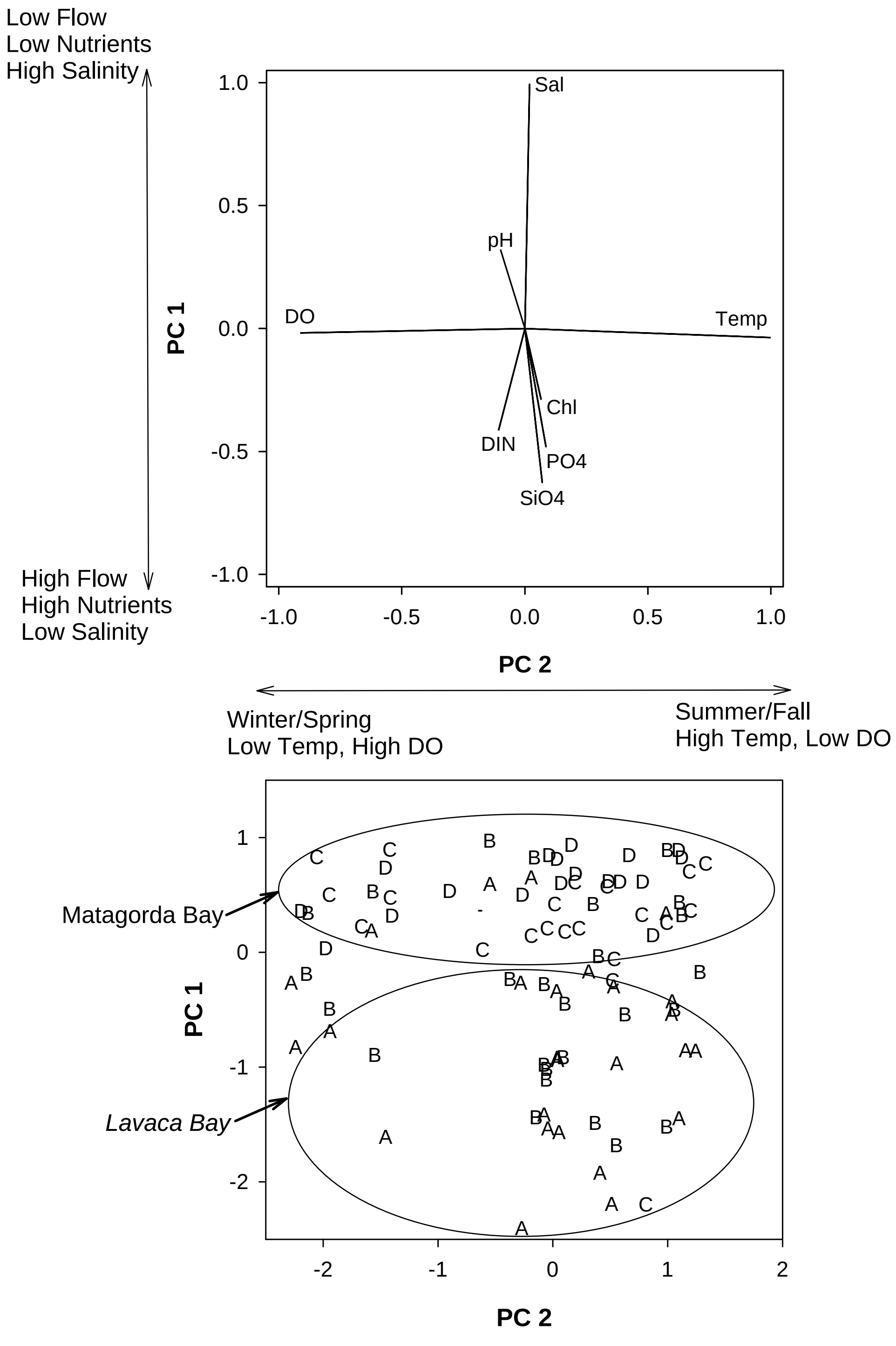


**Figure 5.2-3 Multivariate Analysis of Water Quality Variables in Lavaca Bay and Matagorda Bay**

Top: Variable loads showing contribution to PC scores. Abbreviations: Sal = salinity, pH = pH, DO = dissolved oxygen, Temp = temperature, SiO4 = silicate, PO4 = phosphate, DIN = dissolved inorganic nitrogen, Chl = chlorophyll a.
Bottom: Station scores showing salinity habitat zones.
Source: Pollack et al. 2009.

## Table 5.2-1 Matagorda Bay Nitrogen Budget (metric tons/year)

Source: MBHE. 2005.

| | 1984 | | 1987 | | 2001 | |
|---|---|---|---|---|---|---|
| | Pre-Diversion | Post-Diversion | Pre-Diversion | Post-Diversion | Pre-Diversion | Post-Diversion |
| **Matagorda Bay** | | | | | | |
| Direct Inputs | | | | | | |
| Colorado River | 666 | 1,241 | 2,261 | 7,474 | 1,549 | 3,526 |
| Navidad River | 353 | 353 | 770 | 770 | 804 | 804 |
| Lavaca River | 165 | 165 | 947 | 947 | 932 | 932 |
| Tres Palacios River | 262 | 262 | 185 | 185 | 286 | 286 |
| Garcitas/Placedo Creeks | 96 | 96 | 209 | 209 | 194 | 194 |
| Ungaged Flows | 1,454 | 1,454 | 1,788 | 1,788 | 2,739 | 2,739 |
| Wastewater | 111 | 111 | 111 | 111 | 111 | 111 |
| Precipitation | 95 | 95 | 351 | 351 | 297 | 297 |
| Dry deposition | 330 | 330 | 596 | 596 | 596 | 596 |
| Subtotal In | 3,532 | 4,107 | 7,218 | 12,431 | 7,506 | 9,484 |
| Bio-geochemical Losses | | | | | | |
| Denitrification | 1,355 | 1,355 | 1,355 | 1,355 | 1,355 | 1,355 |
| Burial in Sediments | 60 | 60 | 410 | 410 | 323 | 323 |
| Fisheries Harvest | 82 | 82 | 97 | 97 | 93 | 93 |
| Escapement | 104 | 104 | 208 | 208 | 182 | 182 |
| Subtotal Loss | 1,601 | 1,601 | 2,070 | 2,070 | 1,953 | 1,953 |
| **East Matagorda Bay** | | | | | | |
| Direct Inputs | | | | | | |
| Colorado River via GIWW | 350 | 326 | 786 | 738 | 650 | 606 |
| Ungaged Flows | 1,708 | 1,708 | 982 | 982 | 2,359 | 2,359 |
| Precipitation | 20 | 20 | 72 | 72 | 61 | 61 |
| Dry deposition | 68 | 68 | 123 | 123 | 123 | 123 |
| Subtotal Inputs | 2,145 | 2,122 | 1,964 | 1,916 | 3,193 | 3,149 |
| Bio-geochemical Losses | | | | | | |
| Denitrification | 279 | 279 | 279 | 279 | 279 | 279 |
| Burial in Sediments | 12 | 12 | 84 | 84 | 66 | 66 |
| Fisheries Harvest | 17 | 17 | 20 | 20 | 19 | 19 |
| Escapement | 21 | 21 | 43 | 43 | 37 | 37 |
| Subtotal Loss | 330 | 330 | 426 | 426 | 402 | 402 |
| Export to Gulf by Difference | 3,746 | 4,298 | 6,685 | 11,851 | 8,344 | 10,278 |
| Direct Export to Gulf | 636 | 85 | 5,447 | 282 | 2,141 | 208 |
| Total Export to Gulf | 4,382 | 4,382 | 12,132 | 12,132 | 10,485 | 10,485 |

Note: 1984 considered relatively dry, 1987 relatively wet and 2001 employed as an average year.

## Table 5.2-2 Matagorda Bay Organic Matter Budget (metric tons/year)

Source: MBHE. 2005

| | 1984 | | 1987 | | 2001 | |
|---|---|---|---|---|---|---|
| | Pre-Diversion | Post-Diversion | Pre-Diversion | Post-Diversion | Pre-Diversion | Post-Diversion |
| **Matagorda Bay** | | | | | | |
| Direct Inputs | | | | | | |
| Colorado River | 12,990 | 31,849 | 57,729 | 241,071 | 34,550 | 88,888 |
| Navidad River | 8,177 | 8,177 | 17,820 | 17,820 | 18,601 | 18,601 |
| Lavaca River | 4,121 | 4,121 | 54,249 | 54,249 | 50,556 | 50,556 |
| Tres Palacios River | 17,876 | 17,876 | 9,985 | 9,985 | 18,702 | 18,702 |
| Garcitas/Placedo Creeks | 4,872 | 4,872 | 14,810 | 14,810 | 13,596 | 13,596 |
| Ungaged Flows | 79,183 | 79,183 | 88,901 | 88,901 | 172,899 | 172,899 |
| Wastewater | 56 | 56 | 56 | 56 | 56 | 56 |
| Subtotal In | 127,274 | 146,134 | 243,549 | 426,892 | 308,959 | 363,298 |
| | | | | | | |
| Bio-geochemical Losses | | | | | | |
| Burial in Sediments | 951 | 951 | 6,499 | 6,499 | 5,112 | 5,112 |
| Fisheries Harvest | 1,300 | 1,300 | 1,537 | 1,537 | 1,478 | 1,478 |
| Escapement | 1,648 | 1,648 | 3,297 | 3,297 | 2,885 | 2,885 |
| Subtotal Loss | 3,899 | 3,899 | 11,333 | 11,333 | 9,474 | 9,474 |
| | | | | | | |
| **East Matagorda Bay** | | | | | | |
| Direct Inputs | | | | | | |
| Colorado River via GIWW | 5,586 | 5,286 | 16,305 | 15,547 | 13,038 | 12,292 |
| Ungaged Flows | 134,306 | 134,306 | 52,228 | 52,228 | 191,164 | 191,164 |
| Subtotal Inputs | 139,892 | 139,592 | 68,533 | 67,775 | 204,202 | 203,457 |
| | | | | | | |
| Bio-geochemical Losses | | | | | | |
| Burial in Sediments | 196 | 196 | 1,339 | 1,339 | 1,053 | 1,053 |
| Fisheries Harvest | 268 | 268 | 317 | 317 | 304 | 304 |
| Escapement | 340 | 340 | 679 | 679 | 594 | 594 |
| Subtotal Loss | 803 | 803 | 2,335 | 2,335 | 1,952 | 1,952 |
| | | | | | | |
| Export to Gulf by Difference | 262,464 | 281,023 | 298,415 | 481,000 | 501,736 | 555,328 |
| Direct Export to Gulf | 20,276 | 1,717 | 189,387 | 6,802 | 58,287 | 4,694 |
| Total Export to Gulf | 282,740 | 282,740 | 487,802 | 487,802 | 560,022 | 560,022 |

Note: 1984 considered relatively dry, 1987 relatively wet and 2001 employed as an average year.

for a relative dry (1984), wet (1987) and average year (2001) and effect of the river diversion constructed between 1988 and 1992. The bulk of the wastewater N load is incorporated in the Colorado River flows so the explicit wastewater contribution is relatively small. The inputs include particulate forms of N that become part of the sediment, which provides a valuable buffer to bay nutrient concentrations. Some of this N in the sediment is released in dissolved inorganic forms and some is lost to denitrification. The denitrification rate shown in the table was developed from available measurements and not scaled for different levels of inflow. The organic matter budget is similar except that some terms such as precipitation do not apply. The organic matter budget involves an attempt to represent the contribution of macro-detritus (branches and other organic matter too large for normal sample bottles) by doubling the volatile suspended solids (VSS) loads concentration. Similar budgets have been produced over the years by TWDB and TPWD for all of the bay systems (see Appendix A). These budgets would need updating, but with the availability of data today, updating the input data would be a relatively modest undertaking, and various programs do exist to calculate such loads, e.g., SPARROW and LOADEST[7]. However, developing information on processes such as sediment interactions and transfers to the Gulf would be more complex.

Examples of the long-term trend in key bay processes are more limited. A long-term trend analysis was not performed for the LCRA/SAWS Water Project because the main focus was on maintaining the conditions after the most recent major modification, the Colorado River diversion. A limited long-term trend example is available for N inputs to Galveston Bay as affected by population growth in the watershed, reservoir development, and improvements in wastewater treatment (Figure 5.1-4). These processes caused major changes in the N inputs to the Galveston Bay system. In addition, there were major changes in Gulf water exchange and bay volume during the period due in part to significant navigation channel development. Since the long-term trend analysis was performed in 1990, it is somewhat dated. But with those limitations, it makes the point that changes in what is carried by inflows can be significant and potentially important. A similar kind of analysis can be produced using population and other changes in the watershed with relatively modest effort.

## 5.3 INTEGRATION OF ESTUARINE INFLOW AND RIVERINE FLOW RECOMMENDATIONS

Under Senate Bill 3, BBESTs are required to develop environmental flow recommendations for protecting both riverine instream uses and estuarine aquatic resources. Considered separately, this twofold directive has the potential to generate inconsistent flow recommendations near the mouths of major rivers because of the different methodologies that may be used for analyzing these different types of aquatic ecosystems. There is also the distinct possibility that the environmental flow recommendations for either one of these two aquatic systems could be adequate to provide the necessary flows for the other.

Because of the distinct differences between riverine and estuarine ecosystems, requirements for environmental flows also are distinctively different. While a single approach or methodology potentially could be applied to estimate environmental flow requirements for these different

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[7] http://water.usgs.gov/nawqa/sparrow/
http://water.usgs.gov/software/loadest/

systems (such as the HEFR hydrology-based method), different input parameters would have to be established for each system in order to appropriately describe important components of the flow regimes considered necessary to protect the different ecosystem features.

Regardless of the approach or approaches applied to estimate the environmental flow requirements for protecting the instream uses in the lower reach of a river and for providing the necessary freshwater inflows to its associated estuary or bay, it would seem that the logical process for resolving inconsistencies in the flow requirements operationally would be to err on the conservative side by always implementing the more restrictive of the two. This would ensure that both types of flow regimes would always be satisfied. However, there still may be site-specific circumstances or conditions that may warrant some modification of the individual environmental flow requirement, and this would have to be addressed on a case-by-case basis.

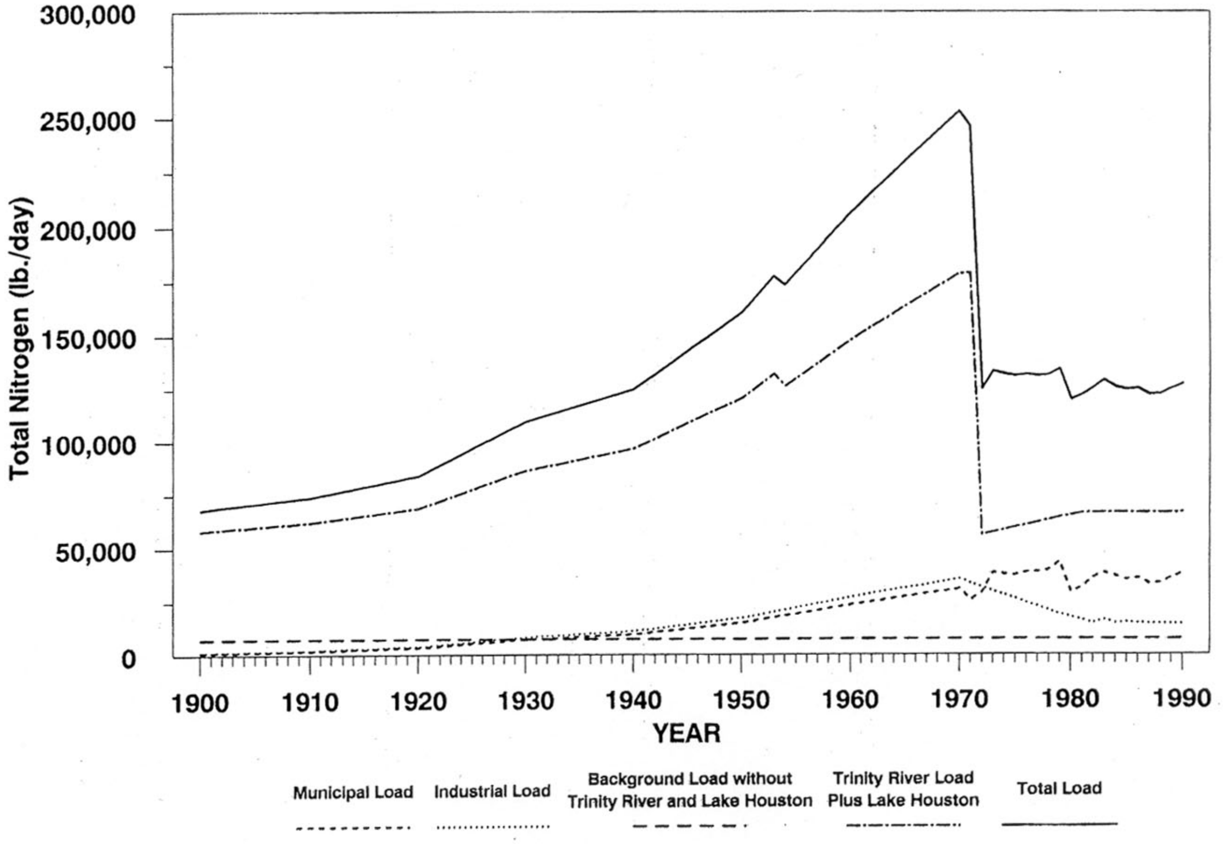

**Figure 5.2-4 Total Nitrogen Load to Galveston Bay**
Source: Jensen et al. 1991

# SECTION 6
# SUMMARY AND RECOMMENDATIONS

The focus of this document is on the importance of freshwater inflows for protecting aquatic resources in bays and estuaries along the Texas coast and on methodologies that might be considered by the BBESTs for developing freshwater inflow regimes pursuant to the requirements of Senate Bill 3.

Senate Bill 3 provides that the BBESTs must develop an environmental flow analysis and "a recommended flow regime for the . . .bay system". The legislation defines an environmental flow regime as a "schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support the sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies. Such inflow regimes will have to be developed by BBESTs recognizing the inherent variability in hydrometeorological conditions that contributed to and have sustained these productive estuarine ecosystems over time.

The foregoing sections have provided information on the estuarine characteristics considered vital to understanding how freshwater inflow regimes affect the ecological health of Texas bays and estuaries (Section 2); a guide to the data, information and tools that are currently available from the State Methodology to help develop freshwater flow recommendations (Section 3); and a description and analysis of available methodologies for developing inflow regime recommendations (Section 4). Section 5 presents other considerations that the BBEST should review when formulating its flow regime recommendations. The SAC provides the following summary and recommendations from the information presented herein:

## The Estuarine Ecosystem

- **An estuary is a waterbody on the boundary of the oceanic and terrestrial environments, and is transitional between freshwater and marine.**

  The major Texas estuaries are coastal embayments, broad systems with complex morphology that develop internal circulations important in the distribution of waterborne constituents and biological populations. The functional components of the estuary ecosystem may be usefully classified as hydrodynamic (the currents and circulations within the system), waterborne constituents (the materials and chemical compounds carried in solution or suspension within the estuary waters, whose levels determine suitability of the water for use by organisms), and biology (the various organisms ranging from microscopic to macroscopic, that inhabit the estuary).

- **Of central importance to the estuarine environment is the exchange with the ocean.**

  The exchange between estuary and sea is controlled by tides, seasonal water-level excursions, gravity currents and meteorology (especially wind stress) as well as the morphology and dimensions of the inlet(s) connecting the estuary to the sea. A direct measure of the physical exchange with the sea is the salinity distribution within an estuary. Salinity is the quintessential estuary parameter. The range and distribution of salinities can therefore be important demarcators of suitable habitat for estuarine species. The spatial estuarine gradient is fundamental for regulating differences in the ecological functions, habitats, and integrity of the estuary along the salinity gradient.

Exchange between estuary and sea also manifests itself in the organisms. Many of the important Gulf of Mexico animals, notably major fish and shellfish species, are "estuarine dependent" meaning that they migrate between the sea and the estuary at various life-history stages.

- **Freshwater inflow affects the estuary through multiple mechanisms**

  Freshwater inflow serves a variety of important functions to coastal estuarine ecosystems by creating and preserving low-salinity nurseries, transporting sediments, nutrients, and allochthonous organic matter downstream, and affecting estuarine species movements and reproductive timing.

- **The estuary is influenced by multiple factors, one of which is freshwater inflow**

  There is a central difference between the roles of flow in the river or stream, and in the estuary, with regard to protecting environmental resources. In the riverine setting, flow is the dominating variable that controls almost all of the hydrographic and biological processes. In the estuarine setting, inflow is one of several variables, such as exchanges with the sea driven by tides and winds, internal circulations driven by density differences, wind set-up, and channelization, all of which can influence biology, in addition to the interaction of marine and estuarine populations (both flora and fauna). There are many processes acting within the estuary, which respond to these multiple external factors, that determine the levels and distributions of waterborne substances and the locations and viability of organisms. While freshwater inflow is only one variable in this complexity, it is a very significant variable in terms of overall health of the estuary and is the focus of Senate Bill 3 requirements.

### Setting Realistic Expectations

- **To infer the relation between inflow and the ecosystem, some type of model(s) will be needed.**

  While *deterministic* models of complex estuarine ecosystem processes have been under development for at least half a century, there remain major theoretical and operational difficulties in their application, as well as a requirement for data that may not exist. No comprehensive model encompassing all estuarine processes presently exists for any of the Texas estuaries, and will not likely become available within the time frame of the BBESTs' activities. Instead it will be necessary that the BBESTs rely upon sets of measurement from the estuary of concern and accompanying statistical evaluations, perhaps combined with limited deterministic models, to infer responses of the ecosystem to inflows.

- **Without a model representing the full complexity of the estuary ecosystem, inflow effects will have to be treated with an abridged conceptual model retaining only the most salient inflow effects.**

  Given the limited time available to the BBESTs, it is not likely to be feasible to quantify each of the cause-and-effect relations known to be important in estuarine ecosystems. In some systems that have been studied in more detail (e.g. Galveston Bay and Matagorda Bay), more information will exist to help define these relationships, at least in terms of trends and/or basic interactions. In other systems, however, only the most fundamental relations of salinity and some biotic population abundance with inflow and the ecosystem may be feasible for use in determining inflow requirements

  A "conceptual model" of the indirect causal connection between "biology" and "inflow", as diagrammed in Figure 6-1, is suggested to serve as a basis for a technical approach. The "nutrients" and "suspended solids" components are shown in grey to reflect the present thinking of the SAC to address these as *overlays* (see Section 5). The primary determinants are the relation of salinity to inflow coupled with the relation of biology to salinity. It may be possible to establish a direct relation of biology on inflow, as indicated by the broken line of Figure 6-1, though the data requirements and analytical methods will be more demanding.

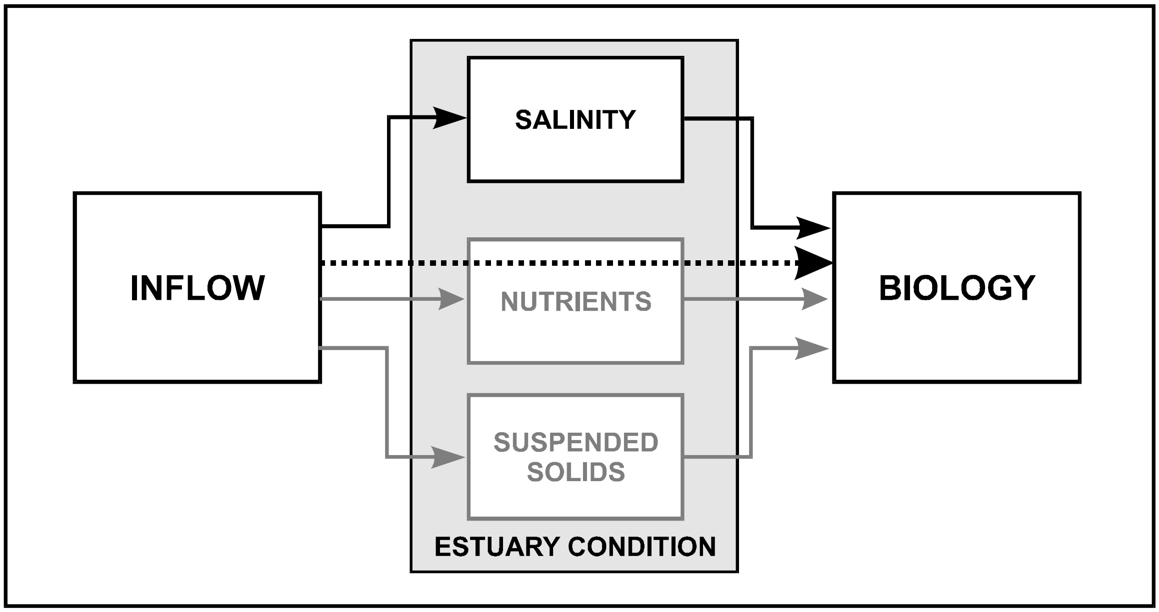

**Figure 6-1 – Schematic of "Conceptual" Relation of "Biology" to "Inflow"**

Biological characterization consists of selection of which biological components are to be addressed and what spatial and temporal formulas are to be used in quantifying the data.

The biological components can be individual species or can be complexes of species, perhaps parameterized by some univariate ecological structural measure such as diversity, or through multivariate analysis. The strategy of Figure 6-1 requires that, once the biological components are identified, either the habitat requirements are delineated, which may be confined to salinity, or that a direct relationship to inflow be developed.

The complexity of the problem that has been simplified in the depiction of Figure 6-1 needs to be borne in mind. The uncertainty implicit in these relationships should be quantified and made part of the analysis.

- **The characterization of inflow data, i.e. how its time/space variation is depicted, is important in identifying major "regime" components and in exposing relations of salinity and/or biology on inflows.**

  Standard depictions can be either cyclic (based upon regularly repeating behavior, such as a seasonal "pattern") or event-based (in which droughts, floods, etc. are separated and quantified), or a combination of the two. Methods employed in the State Methodology are based upon cyclical depiction of monthly inflows. If available, a freshet analysis may prove a useful characterization of estuarine inflows for purposes of assessing the response of biology. Preliminary statistical analyses using seasonal influx events (”freshets”) as an independent variable yield better explanations for the variation of annual-mean abundance for several major species than can be achieved using calendar-period flows.

- **Even though salinity dilution is thought to be a direct function of inflow, when the relation between salinity and inflow is depicted as a simple function it proves to be noisy.**

  A simple statistical relation between salinity and inflow is noisy, because other processes affecting the time variation of salinity are neglected in such an analysis and therefore appear as increased variance. However, this is not to suggest that relating salinity to inflow is subject to so much variance that no inference can be made. Because of the pivotal role that salinity will likely play in the work of the BBESTs, alternative formulations of the independent inflow variable, separated geographically or temporally, should be explored.

## Recommendations

The SAC believes that there exists a combination of methodologies that can be used by the BBESTs to develop scientifically-sound freshwater inflow regime recommendations for the purposes of Senate Bill 3. The recommended regime should be designed to cover the full flow spectrum, from very low flows (near drought-of-record conditions), in which species refuge becomes of primary importance, to higher flow events sufficient to provide adequate nutrient and sediment supply to the bay system for longer-term ecological health. One or more inflow levels between very low and high flows, and their expected frequency of occurrence, should complete, as appropriate, the inflow regime recommendation. These are the essential components of an inflow regime to protect the health and productivity of Texas bays and estuaries while respecting their natural variability.

Specific recommendations are as follows:

- **The scientific objective of the BBESTs should be to quantify as far as possible the cause-and-effect relations diagrammed in Figure 6-1.**

  The diagram of Figure 6-1 is a conceptual model of how changes in inflow will influence habitat, thence biology. The arrows depict causal connections. With these relationships quantified from data, Figure 6-1 would indicate how the effects of a change in inflow would manifest themselves in changes in the selected components of biology. In determining inflow regime recommendations, the BBESTs can in so far as possible: use biological information to define salinity ranges and necessary habitats within the estuary system; analyze field data and/or appropriate hydrodynamic/salinity relationships to define critical salinity refugia at extremely low (near drought-of-record) flows; carry out hydrological evaluations, in combination with salinity and/or biological analyses to characterize suitable mid-to-upper level flows; and apply sediment transport and nutrient input overlay analysis, especially for defining periodic high flow events. The depth and range of each of these determinations will depend upon the availability of information for the particular bay/estuary system.

- **The BBESTs should be cognizant of the extent to which the causal connections of Figure 6-1 can in fact be established from available data and known relationships. Absent this information, the default option is to rely upon inflow data alone, which provides no information on the response of estuary condition or species abundance.**

  Under the circumstance when habitat or key species data are limited (or, perhaps, incapable of being evaluated within the available time frame) or do not yield informative relations, **the evaluation of historical inflow data may be the only means of quantifying an inflow requirement**. This is the default option of Figure 6-1, to be elected only when there is no information on the other elements of the estuarine ecosystem. Even at this, it is still necessary to characterize the inflow, which may involve conceptual models (i.e., hypotheses) of how the biology might respond to inflow, and to formulate specific inflow goals to attain, such as achieving certain statistics of flow variation. This is the basic foundation that underlies the Nature Conservancy/IHA (Section 4.4.1), HEFR (Section 4.3.1), Percent of Flow (Section 4.4.3) and NWF Inflow Pattern (Section 4.3.2), approaches, though the latter does also rely on biological inferences to some degree.

- **When existing data and known relationships exist, the approach to extend the analysis to include estuary condition is sounder than reliance upon inflow data alone**

  Historical hydrological patterns, particularly seasonal, also play an important role in applications of the State Methodology (Section 4.1), the Salinity Zone (Section 4.2), and the LCRA-SAWS Inflow Criteria (Section 4.4.2) methods, but, to varying degrees and levels of sophistication, other factors and relationships pertaining to salinity, species abundance or productivity, nutrients, water quality, and/or sediment loadings also are incorporated into the decision process for determining freshwater inflow requirements.

- **While recognizing the availability of freshwater inflow needs analyses performed by the State agencies for the principal bays of Texas, based on application of the full State Methodology, caution is recommended in interpreting the results as an appropriate basis for Senate Bill 3 environmental flows.**

  Freshwater inflow recommendations have been made for each of the major bay systems by the TPWD and TWDB based upon application of the full State Methodology. The recommended monthly flow patterns (typically the *maxH* flows) are intended to optimize the productivity for a set of key species. However, constraints set in the optimization model tend to dictate the monthly flows, and the resulting pattern of monthly flows does not occur in the historical inflow data record. Moreover, the State Metholology flow recommendations were designed to determine "beneficial inflows", and do not provide an inflow regime consistent with the requirements of Senate Bill 3. Hence, these flow recommendations are not endorsed as satisfactory for the Senate Bill 3 objective of maintaining a sound ecological environment. There are, however, many elements of the State Methodology (see Section 3) and the Verification Methodology, stemming from the comprehensive and valuable studies performed by the TWDB and the TPWD over the years, that are of potential utility to the BBESTs in determining the flow regimes needed to meet Senate Bill 3 objectives.

- **In delineating the ecological state, the maintenance of which is the inflow specification goal, consideration must be given to the present (or relatively recent) nature of the estuary.**

  Whatever method is selected in a particular bay system to produce environmental flow recommendations, it must be recognized that all the bays that we know today have been modified substantially from their historical, natural condition. Maintenance of a sound ecological environment, as required by Senate Bill 3, should consider the evolved bay system, as it is highly unlikely that the bay system will return to some historical natural state. However, understanding the evolution process by which the bay system achieved its current state also is an important aspect of effectively managing and protecting estuarine resources.

- **While it is unlikely that the flow recommendations for the riverine environment and the estuarine environment will be exactly consistent, substantial differences should be closely examined.**

  Under Senate Bill 3, BBESTs are required to develop environmental flow recommendations for protecting both riverine instream uses and estuarine aquatic resources. Considered separately, this twofold directive has the potential to generate inconsistent flow recommendations near the mouths of major rivers because of the different methodologies that may be used for analyzing these different types of aquatic ecosystems. Because the river and bay system in a particular basin evolved under largely the same conditions, a *significant* misalignment between instream and freshwater inflow recommendations should signal the need for a thorough cross-check of the methods. Regardless of the approach or approaches applied to estimate the environmental flow requirements for protecting the instream uses in the lower reach of a river and for providing the necessary freshwater inflows to its associated estuary or bay, it would seem that the logical process for resolving inconsistencies in the flow requirements operationally would be to err on the conservative side by always implementing the more restrictive of the two. This would assure that both types of flow regimes would always be satisfied. However, there still may be site-specific circumstances or conditions that may warrant some modification of the individual environmental flow recommendations, and this should be addressed on a case by case basis.

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# SECTION 8
# CONTRIBUTORS

## *Contributors and Contact Information*

TPWD:
Daniel Opdyke, dan.opdyke@tpwd.state.tx.us
Cindy Loeffler, cindy.loeffler@tpwd.state.tx.us

TWDB:
Mark Wentzel, mark.wentzel@twdb.state.tx.us
Ruben Solis, ruben.solis@twdb.state.tx.us
Carla Guthrie, carla.guthrie@twdb.state.tx.us

TCEQ:
Todd Chenoweth, tchenowe@tceq.state.tx.us
Kathy Alexander, kalexand@tceq.state.tx.us

OTHERS:
Norman Johns, johns@nwf.org

# APPENDIX A
# SUMMARY OF RESULTS OF THE STATE METHODOLOGY FOR THE PRINCIPAL ESTUARIES OF TEXAS

The State Methodology, described in detail in Longley (1994) has two basic management goals based on earlier legislative directives. These are:

1. Ensure the maintenance and productivity of economically important and ecologically characteristic sport or commercial fish and shellfish, and
2. Ensure the maintenance of estuarine life upon which such fish and shellfish are dependent.

The State Methodology addresses the first goal, "maintenance of ... fish and shellfish", by setting a management goal to achieve more than 70% of historical average harvests or abundances of important fish and shellfish. This requirement is set in the Texas Estuarine Mathematical Programming Model (TxEMP) optimization model as a lower constraint, ensuring that flows determined by TxEMP to be valid solutions must meet this requirement. Multiple solutions, where each exceeds the target harvest or abundance, are possible. For each target above the minimum, TxEMP computes the minimum amount of water that meets that target while also meeting other prescribed constraints. Operationally, and equivalently, it determines for a particular annualized volume of water the monthly distribution of that volume required to maximize harvest or abundance while meeting the constraints. TxEMP is the component of the State Methodology that provides viable flow options to be considered for a flow recommendation (Figure A-1).

The State Methodology addresses the second goal, "maintenance ... of estuarine life upon which such fish and shellfish are dependent", in two ways. First, constraints applied in TxEMP recognize the biotic requirements for particular salinity regimes, sediment, nutrients, and habitat. Second, and less explicitly, in the final check of needs salinity levels resulting from the inflow solutions provided by TxEMP are examined at important locations within the estuary (Figure 4-3). This step ensures that the recommended inflows will provide conditions favorable to maintaining the fish, shellfish, and estuarine life upon which they are dependent, *i.e.,* an ecologically healthy system.

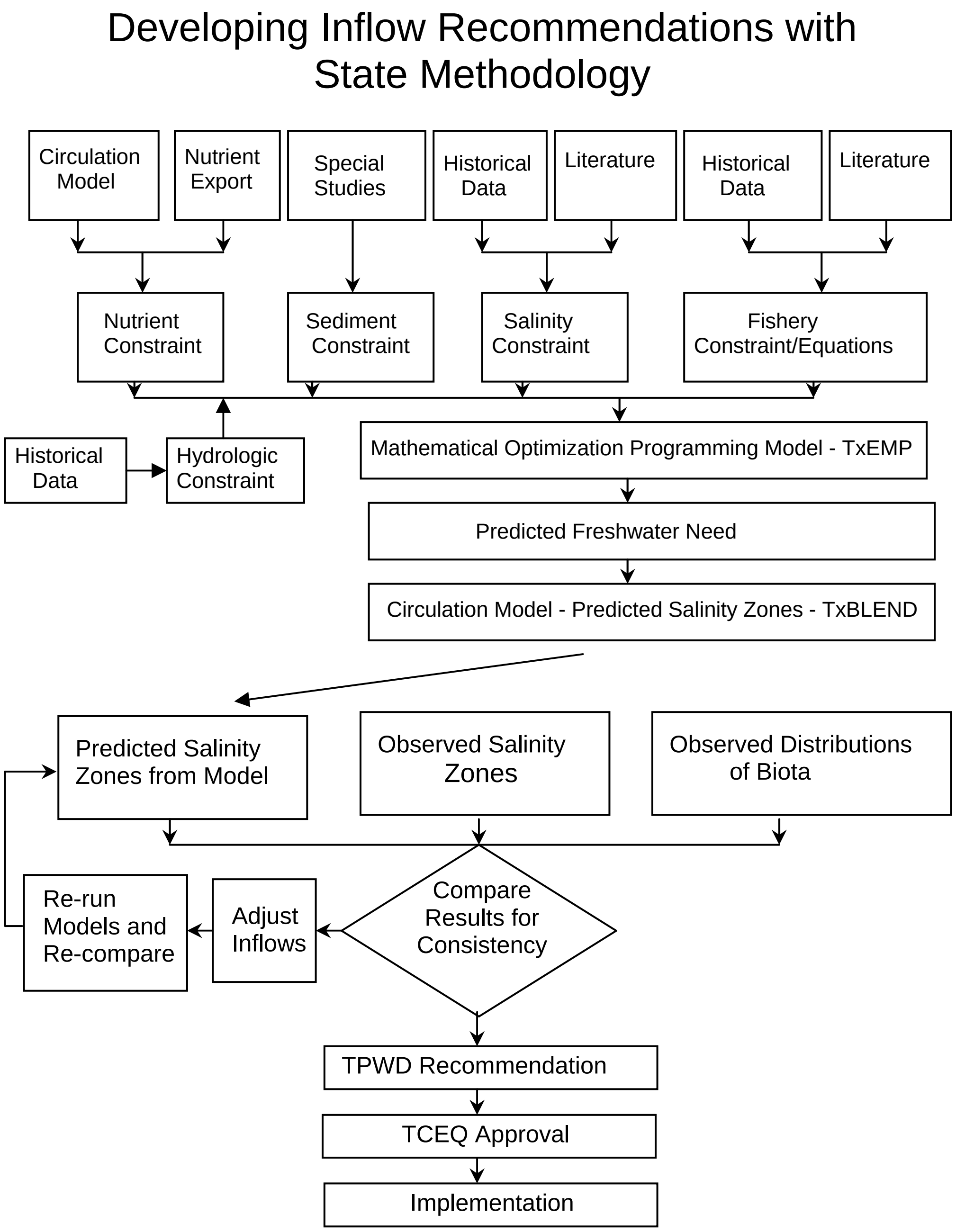


**Figure A-1 State Methodology for Developing Inflow Recommendations**

Management objectives, and management and scientific constraints are input to TxEMP, which provides viable flow solutions. These are then analyzed and considered for the final flow recommendation.

## A-1 Management Objectives

TxEMP can be used to determine flows that achieve different management objectives. These objectives include a subsistence goal (MinQSal) which is the minimum set of inflows that meet only salinity constraints, a maintenance goal (MinQ) which is the minimum set of monthly flows that meet harvest/abundance goals and all hydrological and biological constraints, and an enhancement goal (MaxH or MaxC) which is the set of flows that maximizes harvest/abundance while meeting all hydrological and biological constraints. The final flow recommendations for the major estuaries in Texas as derived using the State Methodology have typically been between MinQ and MaxH.

## A-2 TxEMP Constraints

Constraints are needed to keep TxEMP from producing physically unreachable or ecologically undesirable solutions. Also on a practical level, the model deals only with inflows that are in the range of management options. In water-use permitting, water volumes pertinent to establishing the permit are related to the availability and frequency of particular inflows. Likewise, planning for future inflows to the estuary may require acknowledging the historical range of inflow. Harvest or abundance constraints similarly reflect a management goal for the system that is based on historical data. For example, we may choose to set a constraint which will maintain at least 70% of historical abundance and according to the historical proportions of the target species in the estuary while limiting inflows to less than the historical monthly median.

*Salinity Constraints* - Salinity constraints define one set of upper and lower limits on the TxEMP solution. They are based on the statistical characteristics of salinity within the estuary combined with known salinity preferences and tolerance limits of the target species. Salinity constraints help to ensure that the TxEMP solutions are reasonable and that the management goals are achieved.

*Inflow Constraints* – Inflow constraints are specified as monthly upper and lower bounds and/or seasonal (bimonthly) upper and lower bounds. Upper bounds on monthly inflows generally are set at the median historical monthly flow, while lower bounds are set at the 10th percentile flows.

*Harvest/Abundance Target* – The harvest/abundance constraint is set so that harvest or abundance as calculated by the model is at least some percentage of the historical average (70% and 80% have been used).

*Biomass Ratio (or Relative Abundance)* – This constraint is set to produce solutions which include harvest/catch for a set of species that reflect the historically observed proportions. This is necessary to prevent a solution dominated by a particular species.

*Salinity and Harvest Probability)* – Constraints can be set on the probability that the solution produced meets the salinity or harvest criteria. When probabilities are defined to be high, the model may be very limited in the range of solutions which can be explored.

*Nutrient and Sediment Constraints)* – These constraints are expressed in terms of inflows. To ensure a minimum supply of beneficial nutrients and sediments, constraints can be set on the inflows.

## A-3 Outputs

TxEMP outputs monthly flows that meet the management objectives for harvest or abundance and that meet all the management and biological constraints (Figure A-2). Several solutions meeting different management objectives and points in between are commonly assembled to create a response curve. On that curve, an "annualized" flow represents the sum of the monthly flows obtained by TxEMP as a solution.

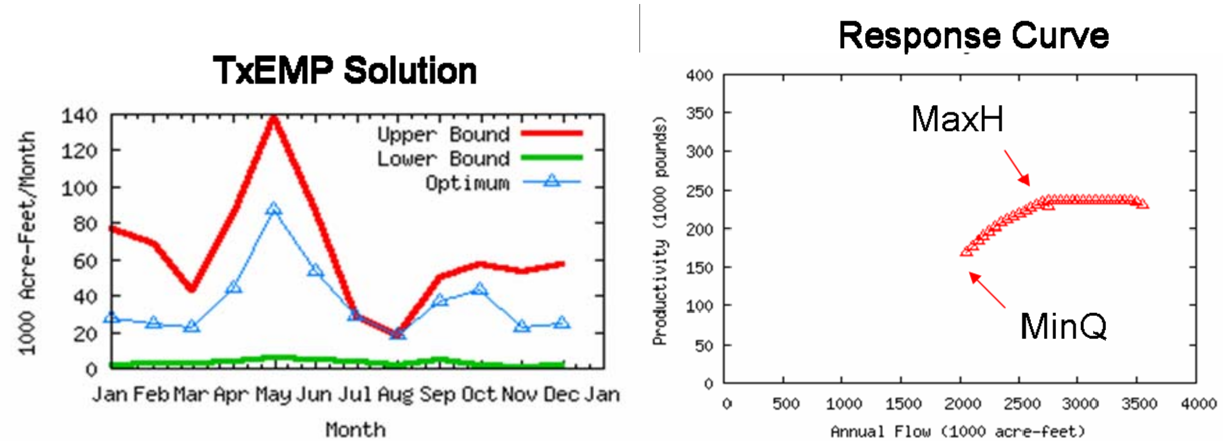


**Figure A-2 Example of Monthly Flow Solution Computed by TxEMP.**

Upper constraint on flow is shown by the red line, lower constraint is shown by the green line. Monthly flow solutions are shown with blue symbols on the left graph. Annualized (sum of monthly flows) flow in the left figure represents a single "annualized" flow volume on the horizontal axis of the Respons Curve in the right graph.

Results from application of the State Methodology to bays and estuaries along the Texas coast are summarized in the following tables. The significant species that have been selected and used to develop freshwater inflow recommendations for different estuarine systems are indicated in Table A-1). Estimated required nitrogen loadings and associated total annual inflows for the different estuarine systems are summarized in Table A-2. Table A-3 presents similar information with regard to sediment loadings. Finally, solutions from the TxEMP analysis in terms of freshwater inflow needs for different management objectives are presented in Table A-4 for each of the major estuaries in Texas.

The State Methodology in effect assumes that it would be possible to manage inflows to the bay/estuarine system such that the “optimized” monthly pattern of inflow would prevail and, thereby, result in maximum, or some other target, species abundance. In reality, due to the wide range of naturally occurring hydrologic and climatic conditions and other factors, that is not likely to be the case. While the State Methodology itself has shortcomings that limit the utility of its results for establishing freshwater inflow recommendations, particularly in the context of a flow regime consistent with Senate Bill 3 directives, the process of developing and applying the State Methodology to individual bay and estuary systems along the Texas coast has produced a wealth of useful data and information that could assist with the development of environmental flow requirements for bays and estuaries pursuant to Senate Bill 3.

## A-4 Decision Points

As described in Longley (1994), decisions about objectives and some constraints applied in TxEMP may be considered to be more in the realm of stakeholder input rather than science; although, it most likely will be a combination of the two that ultimately determines how the State Methodology may be applied to a particular bay and estuary system. Significant decision points that must be addressed in applying TxEMP include the following:

- *Species* to be included and relative *Weighting of Species* - In earlier studies that relied on commercial harvest data, the species included in the analysis consisted of only those where this information was available. More recent studies that rely on TPWD Coastal Fisheries data have included many of the same commercial species, but could include a wider variety of species less weighted towards commercial species. The choice of species used in the analysis is a mix of policy and science.
- *Inflow Constraints* - TxEMP solutions are bound by upper constraints (typically median or mean monthly inflows) to keep the solution reasonable from a management perspective. This constraint could be loosened to explore other viable solutions. The lower flow constraint, typically set as the 10th-percentile monthly flow, could also be varied.
- *Area-Specific Salinity Limits* - Salinity constraints are set and viable solutions are evaluated for areas considered to be important habitat. Decisions on what is considered important habitat is a mix of policy and science.
- *Harvest/Abundance Targets* - Minimum harvest/abundance targets have been set between 70% and 80% of combined historical averages. The target limit is also a mix of policy and science.

## Table A-1 Species Used in Freshwater Inflow Analyses for Major Estuaries

| Species | Sabine-Neches | Trinity-San Jacinto | Lavaca-Colorado | Guadalupe | Mission-Aransas | Nueces | Laguna Madre |
|---|---|---|---|---|---|---|---|
| **Brown Shrimp** | X | X | X | X | X | X | X |
| **White Shrimp** | X | X | X | X | X | X | X |
| **Blue Crab** | X | X | X | X | X | X | X |
| **Red Drum** | X | X | X | X | X | X | X |
| **Atlantic Croaker** | X | | | | | | |
| **Gulf Menhaden** | X | | X | | | | |
| **Spot** | X | | | | | | |
| **Spotted Seatrout** | X | X | | X | | X | X |
| **Eastern Oyster** | | X | X | X | X | | |
| **Black Drum** | | X | | X | X | X | X |
| **Southern Flounder** | | X | | | X | X | X |
| **Striped Mullet** | | | X | | | | |
| **Speckled Trout** | | | | | X | | |
| **Pink Shrimp** | | | | | | | X |

## Table A-2 Nitrogen Loads to Major Estuaries and Their Use for Freshwater Inflow Recommendations

| Estuarine System | Required Total N Load $10^6$ kg N/yr | Basis for Required Loading | Resulting Annual Inflow $10^6$ acre-feet* | Purpose for Which Loading/Inflow Values Were Used |
|---|---|---|---|---|
| Sabine-Neches | 11.4090 | Based on land-use estimated pre-modern average concentration of 0.6 mg TN/l (Omernik, 1976) and historic flows | 10.28 | Reference Value |
| Trinity-San Jacinto** | 15.2680 | Based on land-use estimated pre-modern average concentration of 1.2 mg TN/l (Jensen et al., 1991) and historic flows | 4.27 | Reference Value |
| Lavaca-Colorado** | 13.3600 | Based on requirement to maintain productivity at least 101 g C/$m^2$/yr; Matagorda bay FINS (1997) | 1.71 | Lower Bound on Inflow in TxEMP |
| Guadalupe | 2.4720 | Based on land-use estimated pre-modern average concentration of 0.9 mg TN/l and historic flows | 0.86 | Lower Bound on Inflow in TxEMP |
| Mission-Aransas | 1.6000 | Based on 1977 to 1987 data from TNRCC and USGS | Not Provided | Not Used |
| Nueces** | 0.52 | Based on land-use estimated pre-modern average concentration of 1.35 mg TN/l (Baird et al., 1996; Twidwell and Davis, 1989; Omernik, 1976) and historic flows | 0.12 | Reference Value |
| Laguna Madre | 0.3610 | Based on land-use estimated pre-modern average concentration of 1.0 mg TN/l (Baird et al., 1996; Twidwell and Davis, 1989; Omernik, 1976) and historic flows | 0.07 | Reference Value |

* Assuming no changes in stream concentrations and relative importance of various flows compared to recent (past 20 years) historical data.

** Part of a comprehensive nitrogen budget

## Table A-3 Sediment Loads to Major Estuaries and Their Use for Freshwater Inflow Recommendations

| Estuarine System | Required Total Sediment Load $10^6$ kg/yr | Basis for Required Loading | Resulting Annual Inflow $10^3$ acre-feet* | Purpose for Which Loading/Inflow Values Were Used |
|---|---|---|---|---|
| Sabine-Neches | Not Determined | n/a | n/a | Not Used |
| Trinity-San Jacinto | Not Determined | n/a | n/a | Not Used |
| Lavaca-Colorado | Not Determined | n/a | n/a | Not Used |
| Guadalupe | 225.6215 | Based on offsetting sea-level rise in Mission Lake (Longley and Malstaff, 1994) | 439.38 | Lower Bound onInflow in TxEMP |
| Mission-Aransas | NotDetermined | n/a | n/a | Not Used |
| Nueces | Not Determined | n/a | n/a | Not Used |
| Laguna Madre** | Sediment load with freshwater inflows is insignificant | Based on Morton et al. (1998) | n/a | Not Used |

* Assuming no changes in stream concentrations and relative importance of various flows compared to recent (past 20 years) historical data.

** Part of a comprehensive sediment budget

## Table A-4  Summary of TxEMP Solutions for Major Estuaries

| **Month** | **Sabine-Neches Estuary Sabine Lake** | | | **Trinity-San Jacinto Estuary Galveston Bay** | | | **Lavaca-Colorado Estuary Matagorda Bay** | | | **Guadalupe Estuary San Antonio Bay** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MinQSal | MinQ | MaxC | MinQSal | MinQ | MaxH | CriticalQ* | MinQ | Target Q | MinQSal | MinQ | MaxH |
| January | 438,940 | 624,000 | 1,246,400 | 150,490 | 150,500 | 150,500 | 40,300 | n/a | 319,800 | 52,420 | 111,200 | 111,200 |
| February | 354,300 | 832,500 | 1,539,200 | 216,700 | 216,700 | 155,200 | 40,300 | n/a | 307,900 | 52,420 | 124,200 | 124,200 |
| March | 482,000 | 998,000 | 1,565,780 | 363,900 | 363,900 | 652,800 | 40,300 | n/a | 121,100 | 52,420 | 52,420 | 52,420 |
| April | 416,200 | 778,600 | 1,136,640 | 267,270 | 352,600 | 632,500 | 40,300 | n/a | 141,800 | 52,420 | 52,420 | 52,420 |
| May | 379,800 | 691,900 | 691,900 | 309,970 | 679,700 | 1,273,700 | 40,300 | n/a | 480,100 | 61,000 | 186,050 | 222,600 |
| June | 427,460 | 478,700 | 478,700 | 413,560 | 448,100 | 839,700 | 40,300 | n/a | 376,700 | 60,860 | 135,980 | 162,700 |
| July | 377,550 | 424,470 | 547,300 | 211,500 | 232,700 | 211,500 | 40,300 | n/a | 204,000 | 60,860 | 60,860 | 88,610 |
| August | 427,810 | 361,810 | 466,500 | 140,000 | 154,000 | 140,000 | 40,300 | n/a | 111,700 | 60,860 | 60,850 | 88,330 |
| September | 172,550 | 574,600 | 574,600 | 102,960 | 332,200 | 103,000 | 40,300 | n/a | 206,500 | 52,420 | 52,420 | 52,420 |
| October | 429,090 | 537,900 | 537,900 | 78,600 | 251,900 | 78,600 | 40,300 | n/a | 214,900 | 52,420 | 52,420 | 52,420 |
| November | 378,100 | 237,510 | 237,550 | 164,390 | 351,500 | 351,500 | 40,300 | n/a | 136,900 | 52,420 | 73,830 | 73,830 |
| December | 426,660 | 574,020 | 574,130 | 93,870 | 626,800 | 626,800 | 40,300 | n/a | 128,700 | 52,420 | 66,200 | 66,200 |
| **Annual** | **4,710,460** | **7,114,200** | **9,596,600** | **2,513,210** | **4,158,600** | **5,215,800** | **432,000** | **n/a** | **2,750,000** | **662,920** | **1,028,850** | **1,147,350** |

| **Month** | **Mission-Aransas Estuary Aransas & Copano Bay** | | | **Nueces Estuary Corpus Christi Bay** | | | **Upper Laguna Madre & Baffin Bay** | | | **Lower Laguna Madre & South Bay** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MinQSal | MinQ | MaxH | MinQSal | MinQ | MaxH | MinQSal | MinQ | MaxC | MinQSal | MinQ | MaxC |
| January | 2,940 | 2,940 | 2,940 | 2,230 | 2,230 | 2,230 | 2,080 | 2,080 | 2,080 | 16,950 | 16,230 | 16,230 |
| February | 4,100 | 5,010 | 5,010 | 2,780 | 2,780 | 2,780 | 1,550 | 1,550 | 1,550 | 16,020 | 16,020 | 16,020 |
| March | 3,040 | 3,050 | 3,050 | 4,410 | 4,410 | 4,920 | 1,280 | 1,260 | 1,360 | 16,690 | 16,690 | 19,720 |
| April | 2,950 | 2,430 | 2,430 | 5,180 | 5,180 | 5,180 | 1,210 | 1,200 | 1,290 | 19,170 | 19,170 | 22,650 |
| May | 3,850 | 12,860 | 19,120 | 32,130 | 32,140 | 37,770 | 1,460 | 1,520 | 1,740 | 22,230 | 26,250 | 27,830 |
| June | 2,340 | 10,660 | 15,830 | 9,280 | 19,990 | 36,430 | 940 | 2,010 | 2,300 | 22,090 | 22,090 | 23,000 |
| July | 1,910 | 1,410 | 1,410 | 9,820 | 6,980 | 9,820 | 1,240 | 1,750 | 1,750 | 18,100 | 18,100 | 18,100 |
| August | 1,880 | 2,200 | 1,880 | 9,750 | 9,750 | 9,750 | 1,280 | 1,730 | 1,820 | 15,030 | 15,030 | 15,030 |
| September | 2,750 | 7,360 | 17,650 | 9,600 | 11,040 | 9,600 | 1,490 | 1,490 | 1,490 | 15,510 | 15,900 | 16,720 |
| October | 1,830 | 4,290 | 10,310 | 4,380 | 8,690 | 7,560 | 1,970 | 3,480 | 3,480 | 16,750 | 17,170 | 18,050 |
| November | 2,180 | 3,760 | 3,760 | 6,410 | 7,780 | 7,780 | 1,700 | 1,720 | 2,140 | 16,430 | 16,930 | 18,330 |
| December | 2,780 | 2,780 | 2,780 | 4,670 | 4,670 | 4,670 | 1,770 | 1,770 | 1,770 | 14,920 | 15,370 | 16,650 |
| **Annual** | **32,550** | **58,750** | **86,170** | **100,640** | **115,640** | **138,490** | **17,970** | **21,560** | **22,770** | **209,890** | **214,950** | **228,330** |

* Critical flow is divided between the Lavaca River (4,300 acre-feet/month) and the Colorado River (36,000 acre-feet/month). Target flow is also divided between the two river basins.

# APPENDIX B

## CASE STUDY
## PRELIMINARY COMPARISON OF HEFR FLOW REGIME TO FRESHWATER INFLOWS NEEDS FOR THE GUADALUPE ESTUARY BASED ON THE STATE METHODOLOGY

Senate Bill 3 requires that environmental flow recommendations be developed for both protecting riverine instream uses and providing adequate freshwater inflows to bays and estuaries. This twofold directive has the potential to generate inconsistent flow recommendations near the mouths of major rivers if differing methodologies are used for these two systems. There is also the distinct possibility that the environmental flow recommendations for either one of these two aquatic systems could be adequate to provide the necessary flows for the other, which suggests that a single methodology might be adapted and used for establishing flow recommendations for both riverine and estuarine systems within a given river basin.

This section describes a comparison between HEFR, a potential candidate for establishing instream flow recommendations, and the Texas State Methodology, which has been applied and relied on by the state agencies for estimating freshwater inflow requirements for Texas bays and estuaries, as a proof of concept to determine if, and how, these methodologies could be compared. It should be noted that the values in this report are not final values, they have not been approved by any BBEST or BBASC, and are simply presented here as a proof of concept to facilitate more rigorous comparisons in the future.

The Guadalupe Estuary was selected as the location for this example comparison because of the multitude of studies that have been performed in the basin.

## 1.0 BACKGROUND

Instream flow recommendations and freshwater inflow recommendations can differ in fundamental respects. Instream flow recommendations are typically specified using a daily unit of time with required flow rates expressed in terms of daily average cubic feet per second (cfs). Objectives frequently include maintenance of water quality, provision of adequate habitat for biota, satisfactory movement of sediment, and inundation of riparian habitats. In contrast, freshwater inflow recommendations are typically specified using monthly or longer units of time, with required inflow volumes expressed in acre-feet (ac-ft). Objectives include the establishment of suitable salinity zones for different biota, seasonal patterns of freshets to encourage spawning and migration, influx of nutrients and sediment during high flow periods, and desirable productivity and/or harvest of key estuarine species.

In this case study, instream flow recommendations from HEFR are compared to freshwater inflow recommendations from the State Methodology at a common location to determine if the two can be reconciled.

## 2.0 HEFR APPLICATION TO TOTAL INFLOWS TO GUADALUPE ESTUARY

For this case study, HEFR-based instream flow recommendations were developed that could easily be compared to the State Methodology freshwater inflow recommendations for the Guadalupe Estuary. Because the previous application of the State Methodology to the Guadalupe estuary (including San Antonio Bay) quantified total inflows to the system (excepting direct precipitation and evaporation), the HEFR analysis was performed using the best available estimate of historical total inflows to the system.

Daily flow records are available for the San Antonio River at Goliad since 1924, with continuous recordings since 1939. Daily flow records are available for Coleto Creek near Victoria since 1939, with continuous recordings since 1978. Continuous daily flow records are available for the Guadalupe River at Victoria since 1934. However, runoff downstream of these gages, as well as runoff from coastal basins, is ungaged. These have been estimated using the TxRR Rainfall-Runoff model. The gaged and modeled datasets have been combined with diversion and return flow data in the ungaged areas to develop a water balance for total inflows entering the Guadalupe estuary, as follows:

Total Inflows = Measured Flow in San Antonio River at Goliad
\+ Measured Flow in Guadalupe River at Victoria
\+ Measured Flow in Coleto Creek near Victoria (when gaged)
\+ Modeled Flows (TxRR) from Ungaged Areas
\+ All Return Flows in Ungaged Areas
– All Diversions in Ungaged Areas

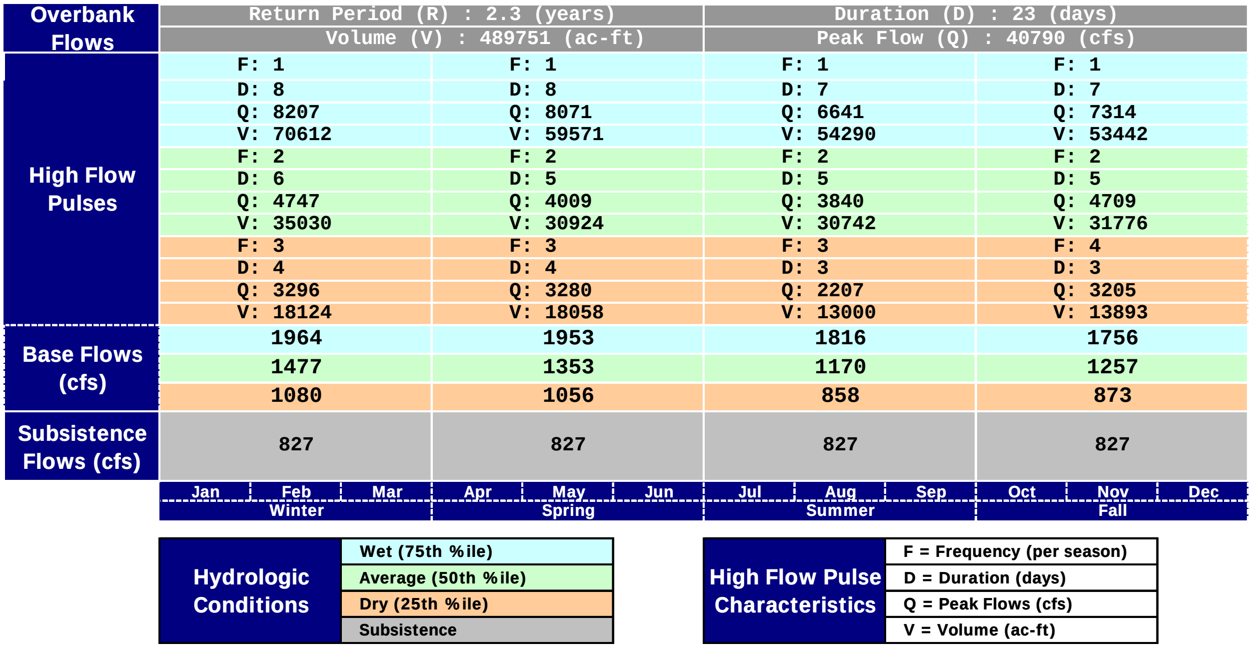
Additional details on these calculations are provided in the TWDB-authored appendix of Pulich et al. (1998).

Daily estimates of such TxRR flows are only available from January 1, 1977 through October 31, 2005. Monthly flow estimates are available prior to 1977, but disaggregating these to appropriate daily values was not deemed necessary for this proof of concept case study. Thus, based on the available data and the fact that HEFR needs to use entire calendar years, the HEFR analysis was run from 1/1/1977 through 12/31/2004.

For this case study, the IHA hydrograph separation and HEFR algorithms were run with the default values listed in Appendix A of SAC (2009a), except that the winter season was specified to start in January. This was chosen to allow the wet spring months of April, May, and June to be grouped together into one season.

The HEFR-input 7Q2 value was set to the sum of the published San Antonio River at Goliad 7Q2 value plus the published Guadalupe River at Victoria 7Q2 value. This resulted in a value of 827 cfs and essentially ignores the other flow contributions in the calculation of 7Q2. The results indicate that the monthly medians of the IHA identified extreme low flows were always less than 827 cfs and thus this summed 7Q2 was specified as the subsistence flow recommendation for each month.

The resulting HEFR matrix is shown in Figure B-1.



| | | | | |
|---|---|---|---|---|
| **Overbank Flows** | Return Period (R) : 2.3 (years)<br>Volume (V) : 489751 (ac-ft) | | Duration (D) : 23 (days)<br>Peak Flow (Q) : 40790 (cfs) | |
| **High Flow Pulses** | F: 1<br>D: 8<br>Q: 8207<br>V: 70612 | F: 1<br>D: 8<br>Q: 8071<br>V: 59571 | F: 1<br>D: 7<br>Q: 6641<br>V: 54290 | F: 1<br>D: 7<br>Q: 7314<br>V: 53442 |
| | F: 2<br>D: 6<br>Q: 4747<br>V: 35030 | F: 2<br>D: 5<br>Q: 4009<br>V: 30924 | F: 2<br>D: 5<br>Q: 3840<br>V: 30742 | F: 2<br>D: 5<br>Q: 4709<br>V: 31776 |
| | F: 3<br>D: 4<br>Q: 3296<br>V: 18124 | F: 3<br>D: 4<br>Q: 3280<br>V: 18058 | F: 3<br>D: 3<br>Q: 2207<br>V: 13000 | F: 4<br>D: 3<br>Q: 3205<br>V: 13893 |
| **Base Flows (cfs)** | 1964 | 1953 | 1816 | 1756 |
| | 1477 | 1353 | 1170 | 1257 |
| | 1080 | 1056 | 858 | 873 |
| **Subsistence Flows (cfs)** | 827 | 827 | 827 | 827 |
| | Jan Feb Mar | Apr May Jun | Jul Aug Sep | Oct Nov Dec |
| | Winter | Spring | Summer | Fall |

| **Hydrologic Conditions** | |
|---|---|
| | Wet (75th %ile) |
| | Average (50th %ile) |
| | Dry (25th %ile) |
| | Subsistence |

**High Flow Pulse Characteristics**

F = Frequency (per season)
D = Duration (days)
Q = Peak Flows (cfs)
V = Volume (ac-ft)

**Figure B-1 HEFR Results for Total Inflows to Guadalupe Estuary**

## 3.0 STATE METHODOLOGY AS APPLIED TO GUADALUPE ESTUARY

The application of the State Methodology for estimating freshwater inflow needs for the Guadalupe estuary is documented in Longley et al. (1994) and Pulich et al. (1998). The resulting inflow recommendations are shown in Table B-1.

MinQSal is conceptualized as a subsistence goal that only meets salinity constraints. MinQ is conceptualized as a maintenance goal that meets harvest/abundance goals and all hydrological and biological constraints. MaxH is conceptualized an enhancement goal that maximizes harvest/abundance and also meets all several biological and hydrological constraints.

**Table B-1 Freshwater Inflow Recommendations for the Guadalupe Estuary and San Antonio Bay Based on the State Methodology**

| Month | MinQSal (ac-ft) | MinQ (ac-ft) | MaxH (ac-ft) |
|---|---:|---:|---:|
| January | 52,420 | 111,200 | 111,200 |
| February | 52,420 | 124,200 | 124,200 |
| March | 52,420 | 52,420 | 52,420 |
| April | 52,420 | 52,420 | 52,420 |
| May | 61,000 | 186,050 | 222,600 |
| June | 60,860 | 135,980 | 162,700 |
| July | 60,860 | 60,860 | 88,610 |
| August | 60,860 | 60,850 | 88,330 |
| September | 52,420 | 52,420 | 52,420 |
| October | 52,420 | 52,420 | 52,420 |
| November | 52,420 | 73,830 | 73,830 |
| December | 52,420 | 66,200 | 66,200 |
| Annual | 662,920 | 1,028,850 | 1,147,350 |

## 4.0 COMPARISON OF HEFR AND STATE METHODOLOGY FLOW RECOMMENDATIONS

HEFR has four flow components (subsistence flow, base flow, high flow pulses, and overbank flows) and four hydrologic conditions (subsistence – subsistence is conceptualized as both a flow component and a hydrologic condition, dry, average, and wet). Two of these components (subsistence and base flows) are relatively steady and lend themselves to comparisons with the monthly State Methodology volumes. However, the other two instream flow components (high flow pulses and overbank flows) are episodic and do not directly compare to the monthly volumes from the State Methodology. Annual volumes of the different flow components produced by the two methods are presented in Table B-2.

To facilitate a useful comparison using these flow components, decisions must be made regarding which month(s) to assign to the high flow pulse and overbank flow components. In the following discussion, comparisons are attempted between flow characteristics under reasonably consistent conditions, e.g., the lowest instream flow recommendation (subsistence) is compared to the lowest freshwater inflow recommendation (MinQSal). High flow pulses and overbank flows are added, as appropriate.

### 4.1 Subsistence Instream Flows Versus MinQSal Freshwater Inflows

The first comparison, shown in Figure B-2, is between flow recommendations under drought or near drought conditions and contrasts subsistence instream flows against the MinQSal inflow recommendations using common units of acre-feet per month (ac-ft/month).

## Table B-2 Annual Volumes of Flow Components for the Guadalupe Estuary and San Antonio Bay Based on the State Methodology and HEFR

| Method, Condition and Components | Annual Volume (ac-ft) |
|---|---|
| HEFR | |
| Subsistence Only | 598,988 |
| Dry Condition | |
| Base Flows Only | 701,923 |
| Base Flows plus High Flow Pulses | 817,549 |
| Base Flows plus High Flow Pulses and Overbank Flows | 1,260,547 |
| Average Condition | |
| Base Flows Only | 953,495 |
| Base Flows plus High Flow Pulses | 1,100,708 |
| Base Flows plus High Flow Pulses and Overbank Flows | 1,531,661 |
| Wet Condition | |
| Base Flows Only | 1,357,596 |
| Base Flows plus High Flow Pulses | 1,488,046 |
| Base Flows plus High Flow Pulses and Overbank Flows | 1,892,649 |
| STATE METHODOLOGY | |
| MinQSal | 662,920 |
| MinQ | 1,028,850 |
| MaxH | 1,147,350 |

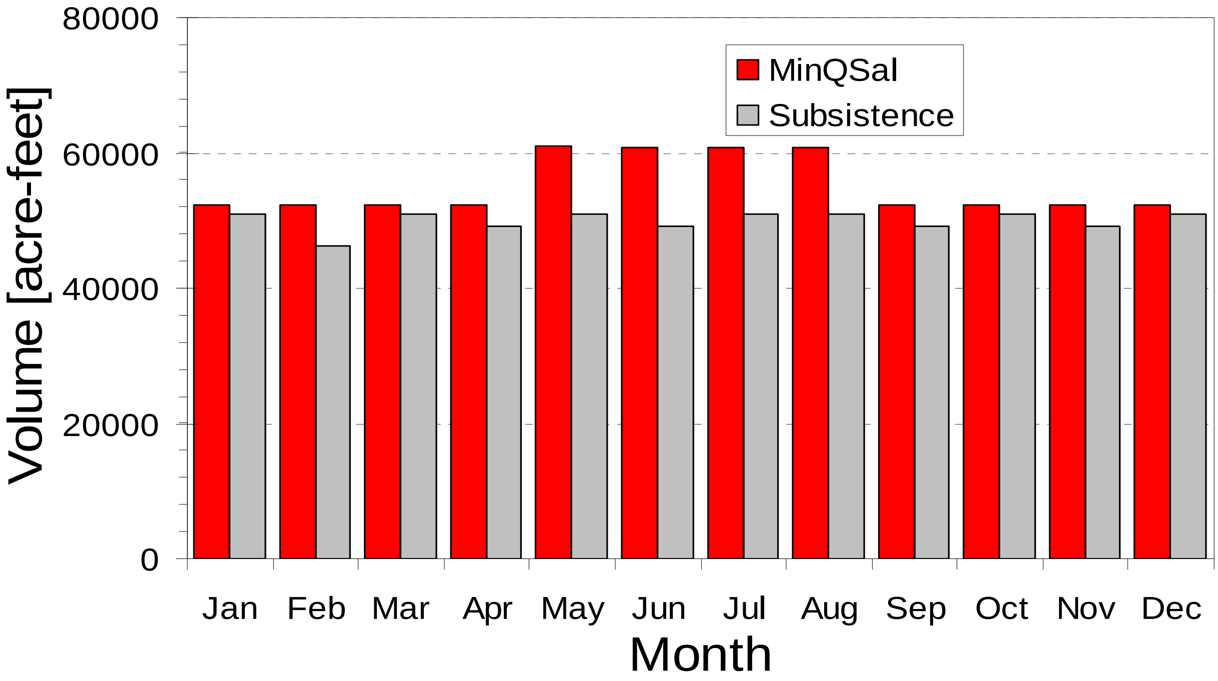


**Figure B-2. Comparison of MinQSal Inflows Versus Subsistence Flow Recommendations**

As shown in Figure B-2, the values are reasonably similar, with the MinQSal values exhibiting some seasonal pattern and always being a little higher than the subsistence flow values. The slight variations in subsistence flow values in Figure B-2 are solely based on the variation in number of days per month, because all of the monthly subsistence flow recommendations were set to the combined 7Q2 value of 827 cfs (see discussion above). In the subsistence hydrologic condition, there are no recommendations for high flow pulses or overbank flows, so none are presented in this figure.

The annualized flow volumes for MinQSal and subsistence flows are 662,920 and 598,988 ac-ft, respectively, which results in about a 10% relative percentage difference.

### 4.2 Dry and Average Instream Flows Versus MinQ Freshwater Inflows

The second comparison, shown in Figure B-3, is between flow recommendations during fairly dry or average, but not drought, conditions. In this figure, the MinQ freshwater inflow recommendation is contrasted with the HEFR estimated base flows under dry and average hydrologic conditions.

The MinQ inflows exhibit greater monthly variation than either of the instream flow recommendations (e.g., Jan/Feb and May/Jun are relatively high whereas Mar/Apr is relatively low). The dry and average base flow recommendations exhibit modest seasonal variations.

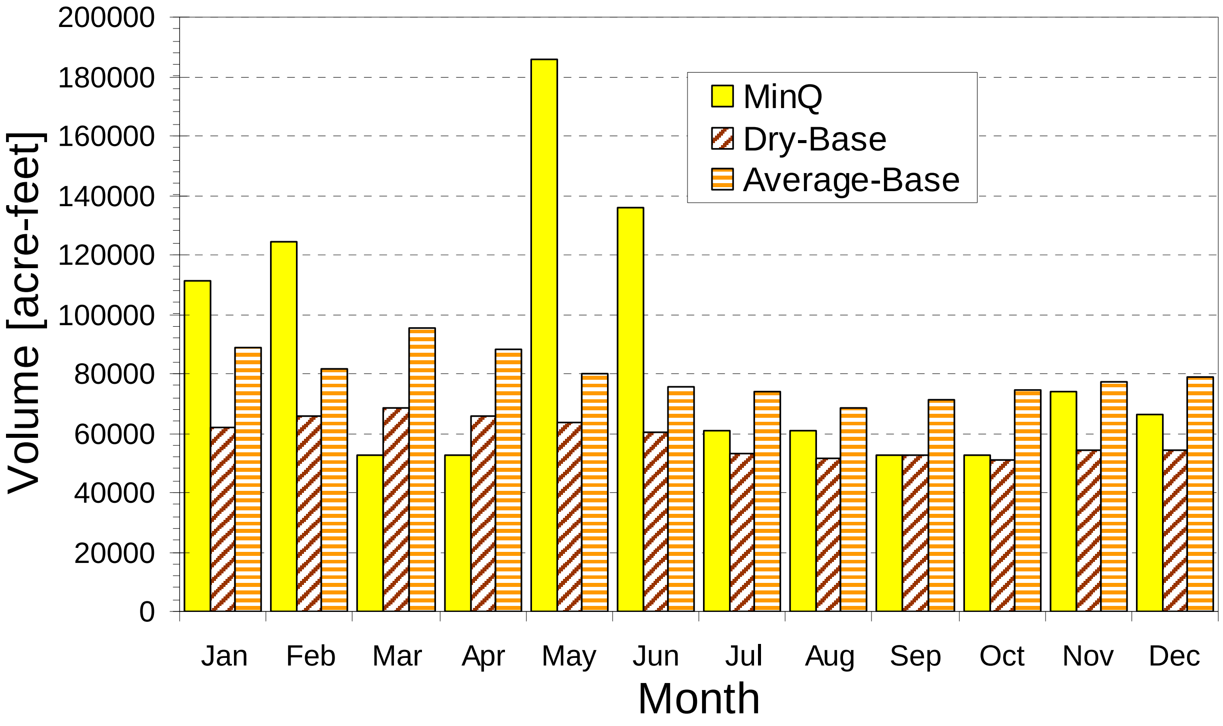


**Figure B-3 Comparison of MinQ Inflows Versus Dry and Average Base Flow Recommendations**

The annualized flow volume for MinQ is 1,028,850 ac-ft. The annualized flow volume for dry base flows is 701,923 ac-ft and the annualized flow volume for average base flows is 953,495 ac-ft. Again, the instream flow recommendations in this comparison are somewhat lower than the freshwater inflow recommendation. The relative percentage difference between the annualized MinQ flow volume and the annualized average base flow volume is about 8%.

Figure B-4 is an extension of Figure B-3 where the high flow pulses have been added. In this figure, dry condition high flow pulses have been added as one to each month, with two in November. The average condition high flow pulses have been added as one to the latter two months of each three month season.

In this instance, the high flow pulses add a modest volume to the instream flow recommendations. In a few months, the addition of the high flow pulse volume caused an instream flow recommendation to go from below MinQ to above MinQ (compare months where the instream flow recommendations exceeded MinQ in Figure B-3 versus Figure B-4. The total annualized flow volume of average base flows plus average high flow pulses is 1,100,708 ac-ft, which now exceeds the MinQ annualized flow volume. The relative percentage difference between these is 7%.

Note that the high flow pulses offset base flow days. In Figure B-3, the June dry base flow is about 60,000 ac-ft. In Figure B-4, the same June dry base flow is just over 50,000 ac-ft, because the four-day long high flow pulse offsets four days of dry base flow (at 1,014 cfs), so the June dry base flow in Figure B-4 is 4×1014×1.98 = 8,030 ac-ft less than the June dry base flow shown in Figure B-3.

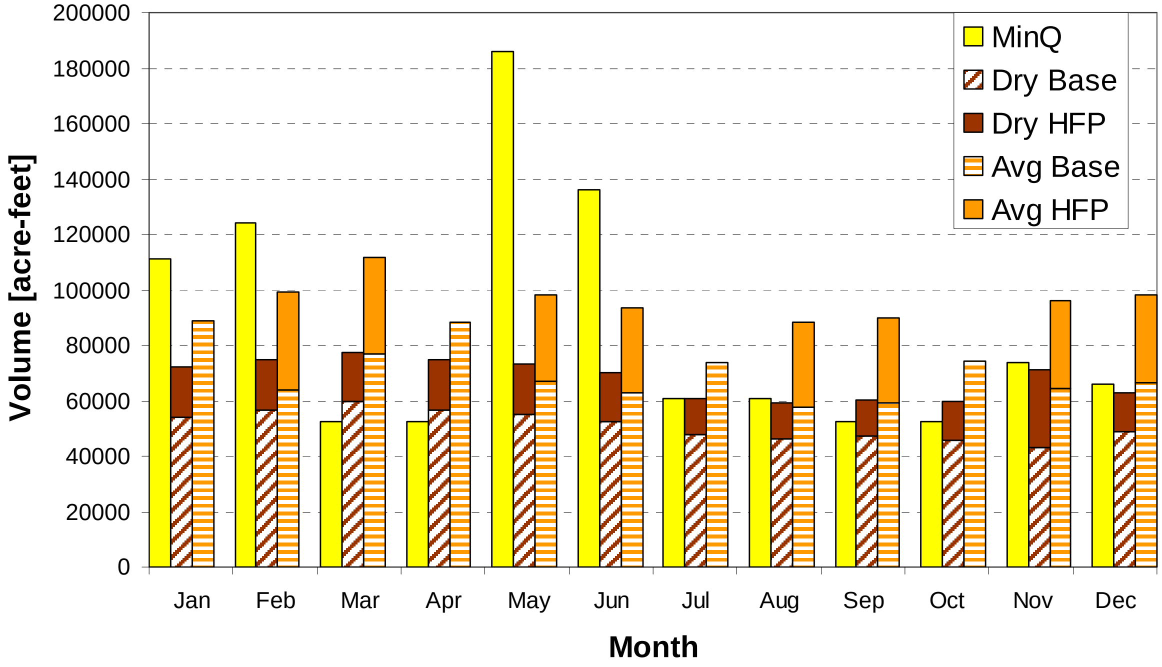


**Figure B-4 Comparison of MinQ Inflows Versus Dry and Average Base Flow Recommendations Plus High Flow Pulse Recommendations.**

Figure B-5 expands this comparison one step further by adding the overbank flow across the months of May and June (assuming an overbank event happens that year). In the total inflows dataset, May had the most overbank flow events (16% of the total) followed by June (with 14% of the total). The overbank flow recommendation has a duration of 23 days. For display purposes, fifteen of those days (and 15/23 of the total overbank volume recommendation) were assigned to May. Eight of those days (and 8/23 of the total overbank volume recommendation) were assigned to June.

In this example, the overbank flows cause both the dry and average conditions to exceed MinQ in the months of May and June.

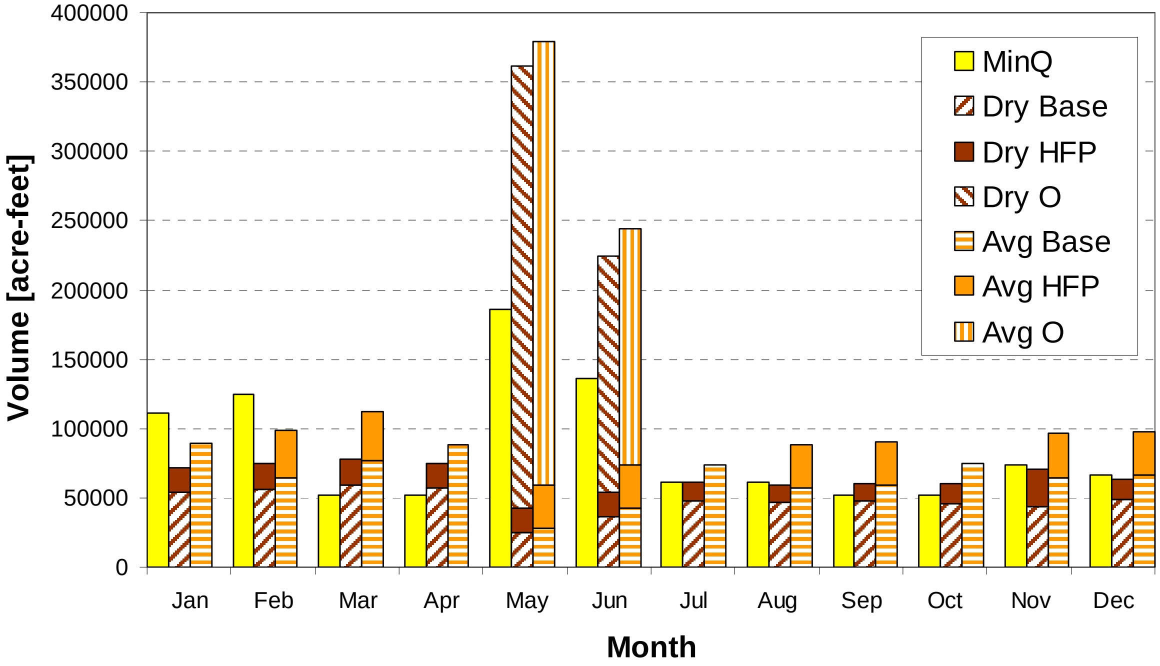


**Figure B-5 Comparison of MinQ Inflows Versus Dry and Average Base Flow Recommendations Plus High Flow Pulse and Overbank Flow Recommendations**

### 4.3 Wet Instream Flows versus MaxH Freshwater Inflows

The third comparison, shown in Figure B-6, is between flow recommendations during somewhat wetter periods. This comparison is between the MaxH freshwater inflow recommendation and the wet condition base flows from HEFR. It is important to remember that MaxH is a constrained optimum value. One of the constraints is that the MaxH inflow cannot exceed the monthly median inflow from the 1941-1987 period of record. Thus MaxH is not particularly representative of "wet" conditions, but it is the highest inflow recommendation from the State Methodology and thus is compared against wet base flows here.

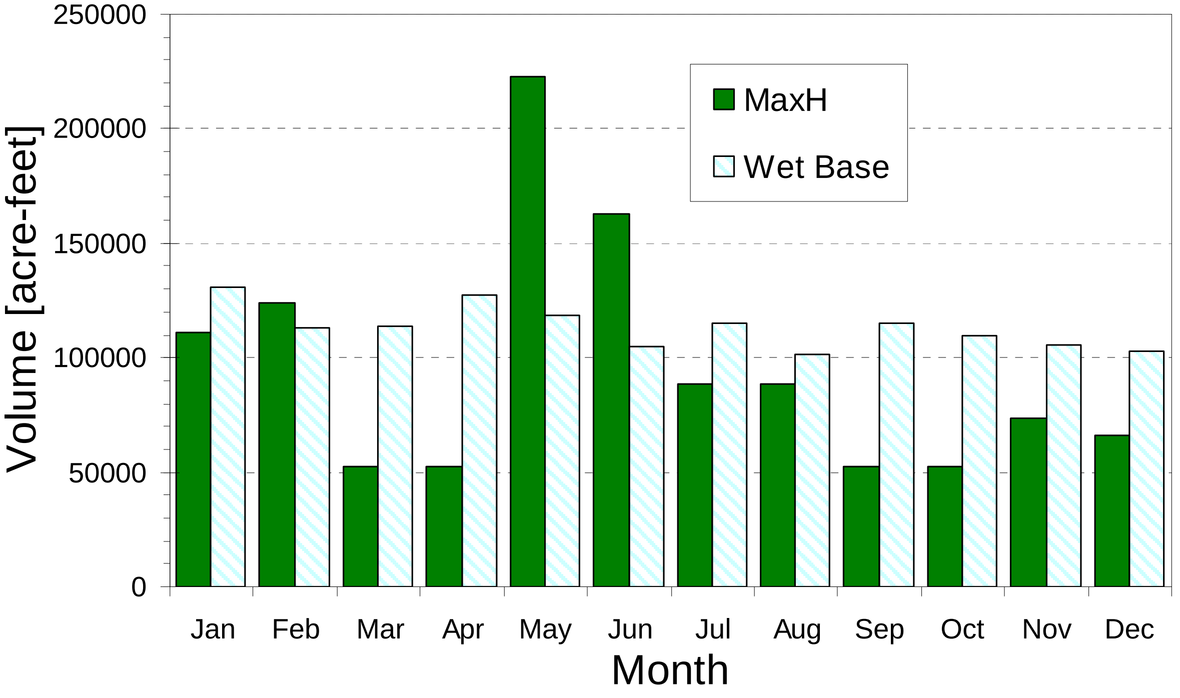


**Figure B-6 Comparison of MaxH Inflows Versus Wet Base Flow Recommendations**

Again, while the HEFR wet base flow results exhibit some seasonal pattern, there is a more pronounced pattern in the MaxH inflow recommendations. In 9 of 12 months, the wet base flow recommendation exceeds the MaxH inflow recommendation. The annualized flow volume for MaxH is 1,147,350 ac-ft. The annualized flow volume for wet base flows is 1,357,596 ac-ft.

Figure B-7 adds high flow pulses and overbank flows to Figure B-6 to provide another comparison to the MaxH freshwater inflows. In this instance, the high flow pulse assigned to February causes the instream flow recommendation to exceed the MaxH inflow in that month. Similarly, the overbank flows assigned to May and June cause the instream flow recommendations to exceed the MaxH inflows in those months.

### 4.4 Salinity Implications of HEFR Flow Recommendations

Salinity has been identified as a key water quality characteristic affecting estuarine productivity (Longley et al., 1994). Log-linear relationships between salinity at three locations and the antecedent monthly total inflows to the Guadalupe estuary were developed in Pulich et al. (1998, pg 60). Salinities computed using these relationships and HEFR-generated flows are provided for two of these sites (Upper San Antonio Bay and Lower San Antonio Bay).

It is important to note that flow recommendations developed through the Senate Bill 3 process will only apply to water right permits that are issued on or after September 1, 2007 (even though many existing water rights already have restrictions that require streamflows to be passed up to

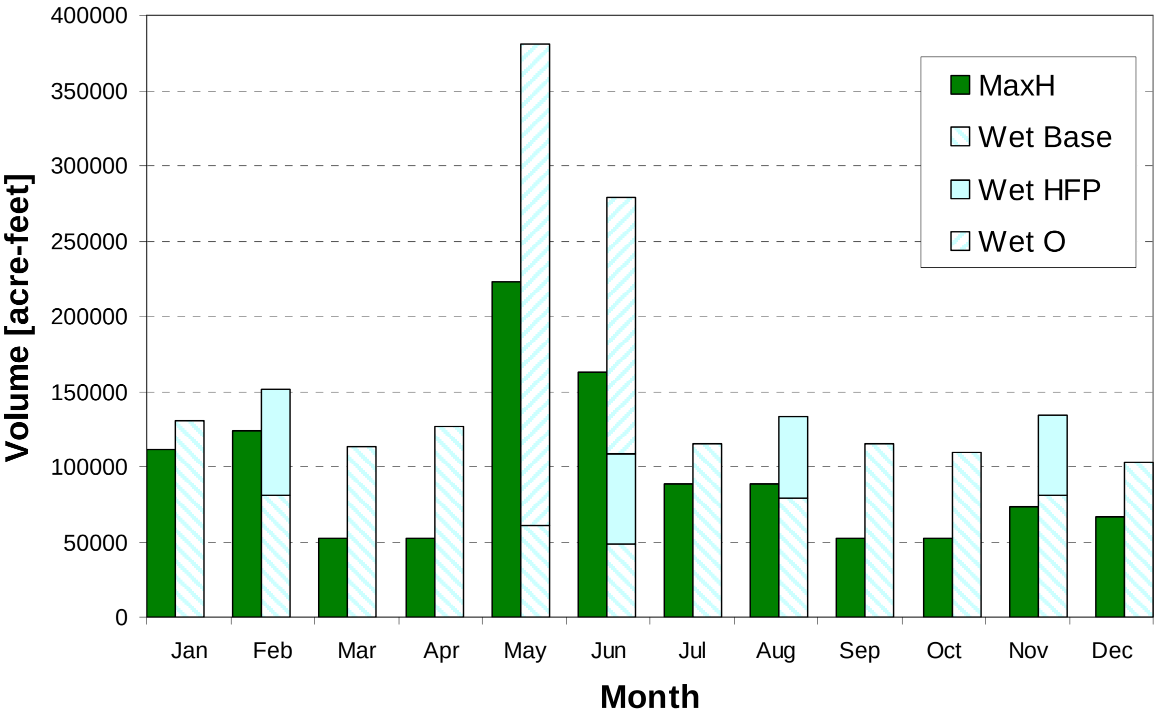


**Figure B-7 Comparison of MaxH Inflows Versus Wet Base Flow Recommendations Plus High Flow Pulse and Overbank Flow Recommendations**

specified environmental flow values). Furthermore, water rights typically do not require the compulsory release of stored water from a reservoir if natural inflows are below the downstream environmental flow recommendations. Thus, this salinity exercise is a hypothetical evaluation of what salinities might look like in future months if flow recommendations were to be met exactly, but should not be interpreted as a realistic prediction of actual future salinity patterns. Actual future salinities, like actual future freshwater inflows, are dependent on a multitude of factors besides just the flow recommendations, including future weather and climate conditions, actual water usage and return flows, groundwater extraction, and watershed development.

Figure B-8 illustrates the various salinity predictions at the Upper San Antonio Bay site (near Seadrift), along with historical monthly medians from two separate datasets (Hist Median TWDB and Hist Median TPWD) and an historical annual median from a third dataset (Longley Annual Median). The data “Hist Median TWDB” were calculated by querying the TWDB datasonde database for the San Antonio Bay site (near Seadrift) and excluding data that have not been QA/QC’d. This process resulted in only data from the late 1980s through the early 2000s, depending on the month, remaining for the analysis. Data were not further processed, thus the presented historical median values represent a partial description of the past behavior of the system. The data “Hist Median TPWD” were calculated by querying the TPWD Coastal Fisheries database in the vicinity of Seadrift, including data from 1991 through 2008. Also shown in Figure B-8 is the annual median salinity value at Seadrift as reported in Longley et al. (1994, pg 29, 3.25 ppt)

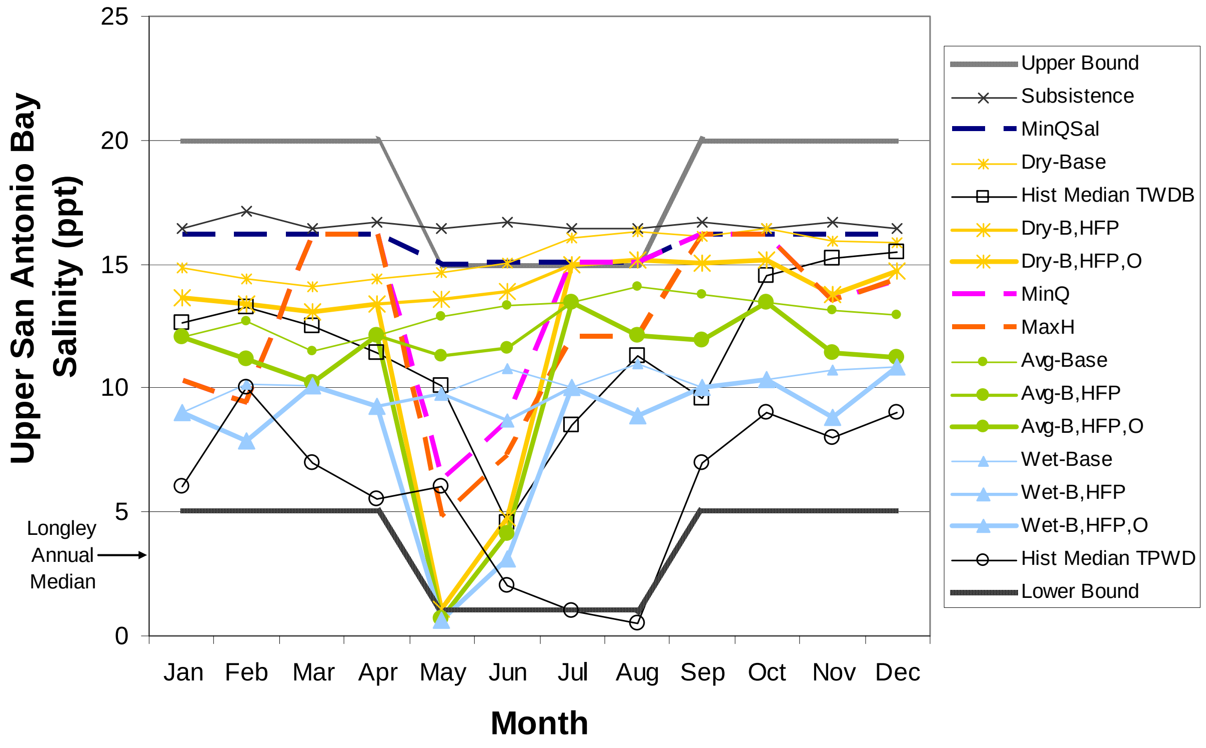


**Figure B-8 Salinity Predictions and Historical Median Salinity Values in Upper San Antonio Bay**

Several observations can be made from this figure:

- Some of the subsistence and dry baseflow recommendations result in salinities that exceed the State Methodology upper salinity bounds in the summer (most notably in July and August), as occurs naturally as well.
- The subsistence flow recommendation results in salinities that equal or slightly exceed the MinQSal predicted salinities.
- MinQ and MinQSal inflows produce salinities that are constrained by and therefore equal to the upper salinity bounds in July and August, whereas all of the dry base instream flow recommendations result in slightly higher salinities for these months (again, which also occurs naturally).
- With overbank flow volumes distributed across May and June, the dry, average, and wet instream flow recommendations result in dramatically lower salinity predictions in these months, as compared to the same categories without overbank flows. In May, these predicted salinities fall slightly below the State Methodology lower salinity bounds.

Figure B-9 illustrates a similar analysis for the Lower San Antonio Bay site. Again, the Longley et al. annual median salinity value (1994, pg 29, 18.46 ppt) is indicated.

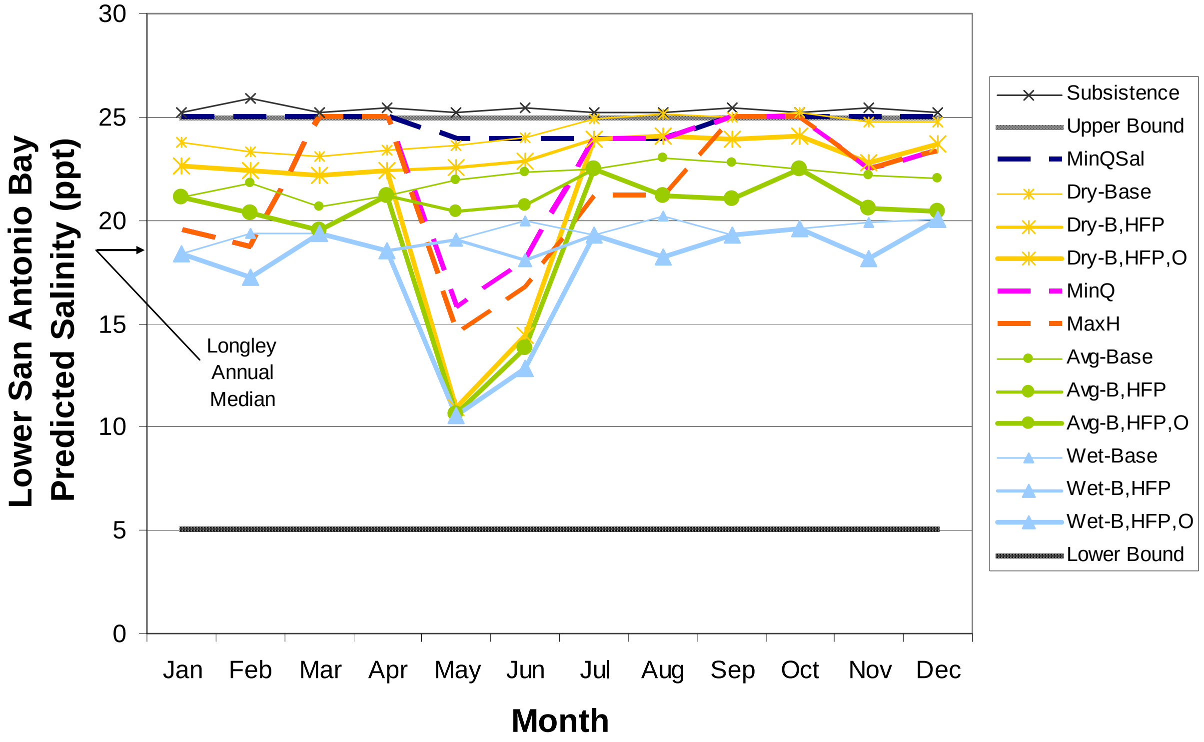


**Figure B-9 Salinity Predictions in Lower San Antonio Bay**

Observations similar to those above can be made from this figure, with some subtle differences. Plus, there are a couple of additional observations:

- All of the subsistence and the July-October dry baseflow recommendations result in salinities that equal or slightly exceed the State Methodology upper salinity bounds.
- All of the subsistence flow recommendations result in salinities that equal or slightly exceed the MinQSal predicted salinities.
- MinQSal inflows produce salinities that are constrained by and therefore equal to the upper salinity bounds from September through April, whereas the MinQ and MaxH inflows produce salinities that are constrained by and therefore equal to the upper salinity bounds in March and April and in September and October.
- With overbank flow volumes distributed across May and June, the dry, average, and wet instream flow recommendations result in dramatically lower salinity predictions in these months, as compared to the same categories without overbank flows.
- None of the predicted salinities from either the State Methodology inflows or the HEFR flow values fall below the State Methodology lower salinity bounds.

## 4.5 Summary and Conclusions

In general, the State Methodology inflow recommendations exhibit more pronounced seasonal patterns than the HEFR results. When graphically displaying the results, the seasonal pattern in HEFR is partly dependent on the month(s) to which the high flow pulses and overbank flows are assigned. Because these recommendations are calculated seasonally (or annually in the case of overbank flows) and the events themselves are episodic, a decision must be made with regards to which month(s) to assign these flow components. The selection makes no difference regarding the annualized flow volume, but does affect the graphical displays of monthly patterns.

The HEFR-generated instream flow recommendations appear to fall within reasonable bounds of conceptually-similar flow recommendations from the State Methodology. Thus, if determined to be necessary or desirable, it appears that these two methods could be reconciled, although the comparison of their individual flow values is confounded by several issues, including:

- Different time scales
- Different objectives
- Absence of frequency recommendations associated with the various State Methodology freshwater inflow levels
- Upper flow constraint (historical median monthly flows) on MaxH inflow values results in MaxH not truly representing wet conditions, as the wet condition instream flow is intended to do

The HEFR-generated salinity values require additional thought. While the calculated values generally stayed between the upper and lower salinity bounds, these bounds alone do not necessarily define estuarine health and productivity. In addition, at the Upper San Antonio Bay site, without overbank events, the instream flow recommendations do not produce the lower salinities in May and June that are identified with the State Methodology. This may or may not be a shortcoming of the HEFR methodology with regard to freshwater inflow requirements.

This case study has presented some graphical comparisons of results for the Guadalupe estuary from the State Methodology and from the HEFR-based approach for developing instream flow recommendations, but is not considered to be a comprehensive presentation of this subject. Still, there is information here that may prove to be useful not only with regard to reconciling differences in riverine instream flow recommendations and estuarine freshwater inflow recommendations, but also possibly with establishing a common approach for developing recommendations for both types of aquatic systems within the timeframe of Senate Bill 3.