

# **FINAL REPORT**

## ***SCIENCE ADVISORY COMMITTEE REPORT ON WATER FOR ENVIRONMENTAL FLOWS***

***Senate Bill 1639  
78<sup>th</sup> Legislature***

**October 26, 2004**

prepared for

**STUDY COMMISSION  
ON WATER FOR ENVIRONMENTAL FLOWS**



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## EXECUTIVE SUMMARY

The question is not whether environmental flows are important and should be protected, but rather, how, when, and where, and in what quantities should flows be reserved for environmental purposes in the state's rivers and streams and its bays and estuaries. The State of Texas has investigated environmental flow issues for several decades. Scientific methods, protocols, and understanding regarding environmental flows have significantly progressed through the course of the previous 40 years and continue to evolve and improve. Due to the complexities of environmental flow issues and continuing advances in scientific understanding, additional work is needed. While the State of Texas has pioneered tools to address freshwater inflow needs for bays and estuaries, there are limitations to these tools in light of both scientific and public policy evolution. To fully address bay and estuary environmental flow issues, the foundation of work accomplished by the state should be improved. While the Texas Instream Flow Studies program appears to encompass a comprehensive and scientific approach for establishing environmental flow needs for rivers and streams across the state, more extensive review and examination of the details of the program, which may not be fully developed until the program is underway, are needed to ensure an effective tool for evaluating riverine environmental flow conditions.

Legislative directive within Texas on environmental flows has also changed over recent decades. This change in directive reflects the evolving state of understanding of the environmental flow problem. In 1985, the Legislature directed the state water agencies to determine sufficient beneficial freshwater inflows "... 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." This is essentially a macro-level approach to the question of sufficient freshwater inflows. The apparent interpretation of this language by the state resource agencies was that it meant to determine inflows that could support key (i.e., a subset of) sport and commercial fish and shellfish species.

By year 2001, within Senate Bill 2, the Legislature directed the state water agencies to "... conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state's rivers and streams necessary to support a sound ecological environment." Addressing a sound ecological environment requires study of the total (complete) aquatic ecosystem and, from a scientific perspective, emphasizes preservation of habitat for desired species as opposed to the state's earlier focus on species abundance. Senate Bill 1639 in the 78<sup>th</sup> Legislative Session continued the Senate Bill 2 theme, identifying "biological soundness" as a goal for the state's waters. Biological soundness should be distinguished from soundness of the hydrologic, geomorphologic, or any of the other natural sciences as it relates to streamflows.

Today, the State of Texas is at a crossroads, where the science of evaluating and determining environmental flows is being comprehensively assessed as a contribution to the state's effort to develop effective environmental flow policy. Based on review of this subject by the Science Advisory Committee, the following observations are offered.

1. A “one-size-fits-all” answer is not correct within Texas. The current climatologic, hydrologic, and aquatic environments vary drastically across the state, meaning some parts are more fragile or more susceptible to harm with small changes in environmental flows. This fact must be acknowledged and considered with respect to scientific study, water management strategy implementation, and regulatory permitting. In the future as in the past, basin and subbasin scientific studies must be devised and then implemented. It is important that in the future the development of environmental flows pursuant to permitting must recognize the essential qualities of specific locations.
2. *Future scientific studies need to focus in more detail on the specific relationship between sound ecological environment and streamflows.* Scientific analysis objectives within the state should be directed toward defining what constitutes a sound ecological environment and the interconnections between streamflows and the biology and hydrography of riverine and estuarine systems. From such scientifically established relations are determined the environmental flows necessary to maintain a sound ecological environment.
3. *Completion of the Texas Instream Flow Studies program and improvement of the bays and estuaries freshwater inflow studies are essential.* Each of these efforts is critical for the state to achieve its goals relative to environmental flows.
4. *Participation by stakeholders and water interests in the environmental flow program and rigorous scientific review are of paramount importance to achieving acceptable environmental flows.* Only through a transparent process can appropriate scientific methods be employed and scientific results be formulated.
5. *For evaluating environmental flows for rivers and streams, statistical desk-top methods and associated technical analyses must be enhanced to facilitate regulatory permitting actions until such time as the Texas Instream Flow Studies program is completed.* The current Lyons and CPC methods appear to have limitations as currently applied. A body of professionals should be charged with review of currently available assessment tools and the development of alternative methodologies for evaluating riverine systems. These enhanced methodologies may also be necessary in the long term as the Texas Instream Flow Studies program may be too resource intensive for every situation.
6. *The TWDB’s State Methodology and the TPWD’s “verification” process used to develop freshwater inflow recommendations for the state’s bays and estuaries exhibit scientific shortcomings that must be addressed.* The measure of abundance used is commercial harvest (except for the recent Sabine Lake recommendations), which has a poor relation to ecological soundness; the various statistical methods employed are questionable, including regression forms and definition of independent variables; the resulting “optimum” inflow regime is mainly determined by constraints, which are arbitrarily specified; and the optimum solution bears no relation to actual harvests, nor do the optimum patterns of inflow occur in the natural hydrology. The TPWD’s verification process is actually a comparative analysis between the *minQ* and *maxH* solutions, and favors the optimal solution with the greater inflow to the bay. One of

the most important questions relating to management of inflows to the Texas bays is unanswered by the State Methodology and the TPWD verification analysis, namely under drought conditions what inflows must a bay receive to maintain its ecosystem over the long term.

7. *Adaptive management and precautionary principle methods must be incorporated into the scientific study, management strategy implementation, and regulatory permitting phases of future environmental flow activities.* History proves that the present science of environmental flows is complex, inexact, and subject to varying levels of uncertainty. These shortcomings identify a need for an overall environmental flow strategy that facilitates change as future information becomes available. Any future adaptive management approach must consider the need for assuring dependable water supplies for human use and must provide reasonable and scientifically-determined boundaries that limit supply risk while also recognizing scientific uncertainty and erring on the side of caution if the risks of environmental damage are high.
8. *There are both regulatory strategies and market-based strategies that can be used to provide for environmental flows.* The state currently has mechanisms for both, but it is not evident that these approaches, as currently structured, are adequate to comprehensively ensure target environmental flows. Further evaluation of existing and alternative regulatory and market-based approaches should be explored to provide for a more comprehensive and effective environmental flow program that addresses both riverine and estuarine needs for the state.

The need for defensible science and acceptable answers relative to the state's environmental flow programs is of paramount importance. While progress has been made, there is work to be done. The Texas Instream Flow Studies program provides the framework for developing scientifically-based basin- and subbasin-specific estimates of environmental flows for rivers and streams across the state, and it needs to proceed following the National Academy of Sciences (NAS) review. Likewise, the data and methodologies being employed for establishing freshwater inflow requirements for the state's bays and estuaries and the results generated need to be thoroughly examined and modified as necessary to provide more scientifically-based answers that are responsive to actual needs of the coastal systems. Less consideration should be given to determining "optimal" levels of freshwater inflow to the bays and estuaries, and more emphasis should be placed on addressing the extreme hydrological events that periodically cause major stresses on the ecological integrity of these systems, notably low-flow and drought conditions.

## **PREFACE**

### **LEGISLATIVE AUTHORITY**

Recognizing the importance that the ecological soundness of the state's riverine and bay and estuarine systems and riparian lands has on the economy, health, and well-being of the state, the Texas Legislature enacted Senate Bill 1639 during the 78<sup>th</sup> Legislative Session that established the Study Commission on Water for Environmental Flows (Study Commission).

In passing this legislation, the Legislature also recognized that the waters of the state are held in trust for the public, and that the right to use state water may be appropriated only as expressly authorized by state law; that the Legislature has expressly required the Texas Commission on Environmental Quality (TCEQ), while balancing all other interests, to consider and provide for the freshwater inflows necessary to maintain the viability of the state's bay and estuary systems in the TCEQ's regular granting of permits for the use of state waters; that the Legislature has not expressly authorized granting water rights exclusively for instream flows dedicated to environmental needs or inflows to the state's bays and estuaries or other similar beneficial uses; and that greater pressures and demands are being placed on the water resources of the state, which makes it of paramount importance to reexamine the process for ensuring that these important priorities are effectively addressed in clear delegations of authority to the TCEQ.

Senate Bill 1639 expressly prohibits the TCEQ from issuing new permits for instream flows dedicated to environmental needs or bay and estuary inflows. However, amendments can be made to existing permits or certificates of adjudication to add a use for instream flows dedicated to environmental needs or bay and estuary inflows.

### **STUDY COMMISSION ON WATER FOR ENVIRONMENTAL FLOWS**

The Study Commission is composed of 15 members, 12 of which have been appointed as follows: two members by the Governor; five members by the Lieutenant Governor; and five members by the Speaker of the House. The three additional members include the presiding officers of the TCEQ, the Texas Water Development Board (TWDB), and the Texas Parks and Wildlife Department (TPWD), or their designees. The appointments of the Lieutenant Governor and the Speaker of the House include one representative of a river authority or municipal water supply entity and one member that represents an entity that is distinguished by its efforts in resource protection. The members of the Study Commission are listed in Table 1.

Senate Bill 1639 requires the Study Commission to conduct public hearings and study public policy implications for balancing the demands on the water resources of the state resulting from a growing population with the requirements of the riverine and bay and estuarine systems, including granting permits for instream flows dedicated to environmental needs or bay and estuary inflows, use of the Texas Water Trust, and any other issues that the Study Commission determines have importance and relevance to the protection of adequate environmental flows. In evaluating the options for providing adequate environmental flows, the Study Commission is charged with considering ways to recognize and account for the strong public policy imperative that exists in

**TABLE 1  
STUDY COMMISSION MEMBERS**

MEMBER	APPOINTED BY
Senator Kenneth Armbrister, Co-Presiding Officer	Lieutenant Governor
Representative Robert R. Puente, Co-Presiding Officer	Speaker of the House
Senator Jeff Wentworth	Lieutenant Governor
Senator Todd Staples	Lieutenant Governor
Representative William A. "Bill" Callegari	Speaker of the House
Representative Charlie Geren	Speaker of the House
Jerry Clark, General Manager, Sabine River Authority	Governor
W.E. "Bill West, General Manager, Guadalupe-Blanco River Authority	Governor
Joseph J. Beal, P.E., General Manager, Lower Colorado River Authority	Lieutenant Governor
Andrew Sansom, Executive Director, International Institute for Sustainable Water Resources, Texas State University	Lieutenant Governor
Dr. Ben F. Vaughan IV, Assistant Professor, Department of Business, Texas Lutheran University	Speaker of the House
David Herndon, Attorney-at-Law	Speaker of the House
Kathleen Hartnett White, Chairman, Texas Commission on Environmental Quality	Legislated
E.G. Rod Pittman, Chairman, Texas Water Development Board	Legislated
Joseph B. C. Fitzsimons, Chairman, Texas Parks and Wildlife Department	Legislated

this state, recognizing that environmental flows are important to the physical, chemical, and biological health of our riverine and bay and estuary systems, and are high priorities in the permitting process. The legislation also requires the Study Commission to specifically address ways that the ecological soundness of these systems will be ensured in the water allocation process.

A report from the Study Commission on its work is due by December 1, 2004. The report is to include summaries of any hearings or studies conducted and any proposed draft legislation recommended by the Study Commission. The Study Commission expires on September 1, 2005.

**SCIENCE ADVISORY COMMITTEE**

To advise and assist the Study Commission, Senate Bill 1639 directs the Study Commission to appoint a Science Advisory Committee (SAC) of no fewer than five and no more than nine members representing a variety of areas of relevant technical expertise. The Study Commission appointed the SAC members listed in Table 2 at its February 18, 2004, public hearing.

**TABLE 2  
SCIENCE ADVISORY COMMITTEE MEMBERS**

MEMBER	ASSOCIATED ENTITY
Dr. Robert J. Brandes, Chairman	R.J. Brandes Company
Dr. B. L. Harris	Texas Water Resource Institute, Texas A&M University
Dr. Larry M. Hauck	Texas Institute for Applied Environmental Research, Tarleton State University
Clay J. Landry	WestWater Research, LLC
Dr. Mitchell L. Mathis	Houston Advanced Research Center
Dr. Paul A. Montagna	Marine Science Institute, University of Texas
Dwight K. Shellman, Jr.	Caddo Lake Institute
Jeff Taylor	City of Houston
Dr. George H. Ward, Jr.	Center for Research in Water Resources, University of Texas at Austin

## **SAC Charge**

The Study Commission has established a charge for the Science Advisory Committee that is comprised of several elements intended to develop and provide technical information for the Study Commission to support its work, pursuant to the requirements of Senate Bill 1639. The specific elements of the charge for the SAC are listed below:

1. Provide a description of the current hydrologic conditions, streamflow patterns across the state in major river basins, and freshwater inflow patterns for major bay and estuary systems along the coast, relative to historical and existing environmental flows.
2. Evaluate the analytical tools and/or procedures that are used or available to assess the requirements for preservation, maintenance, or enhancement of aquatic resources and riparian habitat.
3. Identify ecological parameters or ecosystem characteristics to be considered in determining environmental flow needs for the state's surface water resources and identification of implementation options.
4. Provide any other technical information the Science Advisory Committee feels would be beneficial to the Study Commission on Water for Environmental Flows.

## **SAC Scope of Work**

In response to its charge as set forth by the Study Commission, the SAC has established a Scope of Work that addresses specific technical areas for which information relevant to the environmental flows issue has been compiled, reviewed, and analyzed. A summary of this information has been prepared by the SAC and presented in this report to the Study Commission. Following is a brief discussion and description of each of the study elements comprising the SAC's Scope of Work.

**Surface Water Management in Texas** - The basic concepts of how surface water is managed and accounted for in the state will be addressed and described. This will include an understanding of the prior appropriation doctrine and other water rights systems in place in the state today, the allocation procedures utilized during periods of water shortage among existing water rights, the concept of firm yield with respect to a single reservoir or a system of reservoirs or a direct stream diversion, water availability as it relates to existing and proposed water rights and existing water availability models, water rights permitting procedures and provisions for environmental flows, and water rights enforcement. The TCEQ will assist with the development of this information.

**Current State Agency Roles** - The TCEQ, TWDB, and TPWD have various responsibilities pursuant to the investigation, definition, and maintenance of appropriate levels of environmental flows for the state's riverine, bay and estuarine systems, and these agencies' roles will be reviewed and described. Each of these agencies will provide information to the SAC, describing specific programs and responsibilities relative to environmental flows.

**General Hydrologic Conditions** - Flows in rivers and streams and freshwater inflows to the state's bays and estuaries vary considerably across the state in response to rainfall patterns, evaporation rates, phreatophyte water consumption, watershed runoff characteristics, diversions and return flows by water users, reservoir storage, groundwater recharge and springflows, and other factors. It is important to understand the historical and currently existing trends in flow conditions as part of the overall effort to effectively address the need for maintaining certain levels of environmental flows. Baseline information describing the general time-space variation of surface water hydrology in the state will be assembled and summarized. Various types of flow conditions will be illustrated for specific river basins and bay and estuary systems across the state. The TCEQ, TWDB, and TPWD all have summary information available relative to the general hydrologic conditions in the state that will be useful for addressing this task.

**General Aquatic Ecosystem Conditions** - The general nature and structure of the aquatic ecosystems that comprise the riverine and bay and estuarine systems across the state and the dependence of these ecosystems on various levels of streamflow or freshwater inflow will be addressed and described. Generally, what types of important organisms exist within the different ecosystems and their life stages and interactions within the food web will be discussed. The importance of other naturally occurring factors such as nutrients, salinity, and sediment also will be considered. Information from the TPWD and the TWDB and from other sources will be used in this effort.

**Environmental Flow Tools and Procedures** - The state agencies have been engaged in studies of the requirements for environmental flows since the late 1960s, particularly with regard to freshwater inflows to bays and estuaries. Various tools and procedures for estimating different levels of environmental flows necessary to achieve various levels of protection for environmental resources have been developed and applied for both riverine systems and bay and estuary systems across the state. These methodologies and their results will be reviewed and discussed with the TPWD, TWDB, and TCEQ, and they will be summarized and described relative to those applicable for addressing instream flow requirements for rivers and streams and those applicable for addressing freshwater inflow requirements for bays and estuaries.

This effort will include consideration of results from investigations undertaken by entities other than the state agencies, and it will include a general review of the proposed instream flow program that the three state agencies have devised in response to the legislative requirements contained in Senate Bill 2 (77<sup>th</sup> Legislature, 2001), directing the agencies to ".....conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state's rivers and streams necessary to support a sound ecological environment." All three state agencies will assist the SAC with this assessment by providing information relative to the various methodologies for establishing both instream flows for rivers and streams and freshwater inflows to the bays and estuaries.

**Instream Flow Methodologies** - The review and analysis of instream flow methodologies will necessarily include consideration of the Lyons Method and the Consensus Planning Criteria, both of which are currently used by the state agencies for estimating required levels of environmental flows in streams and rivers. The Lyons Method has been applied primarily by the TCEQ for purposes of establishing minimum environmental flow levels associated with new surface water appropriations. The TWDB has required that the Consensus Planning Criteria be used, as a minimum, to establish environmental flow restrictions (instream flows and bay and



estuary freshwater inflows) for all proposed water development projects considered in the Senate Bill 1 (75<sup>th</sup> Legislature, 1997) regional planning process or requiring state funding support. Examples of the application of the Lyons Method and the Consensus Planning Criteria will be examined. Also, as previously noted, this effort will include a general review of the proposed instream flow program that the state agencies are pursuing in response to the requirements of Senate Bill 2 (which also now is being reviewed by the National Academy of Sciences). Fundamental to this review will be consideration of the scientific basis for these methodologies and their appropriateness for representing conditions throughout the state.

**Bay and Estuary Methodologies** - The TWDB and the TPWD have jointly investigated freshwater inflow needs for all of the major bays and estuaries on the Texas coast. Complex and comprehensive computer modeling procedures have been developed and employed to relate the response of certain estuarine criteria and conditions to various levels of freshwater inflow and to analyze the impact of and the need for different levels and patterns of freshwater inflow. These methodologies will be reviewed and examined in general terms, particularly with regard to their scientific foundation and soundness. Application of these methodologies to certain bays and estuaries and results in terms of indicated requirements for freshwater inflows will be examined.

**Environmental Flow Criteria** - The important ecological parameters and/or ecosystem characteristics that should be considered in determining environmental flow needs for the state's surface water resources will be addressed. This will include identification and discussion of critical ecological relationships involving flows that occur under the widely varying hydrologic and climatic conditions across the state and consideration of the significance of flow and other indicators for maintaining sound ecological environments in riverine systems and the bays and estuaries. An important aspect of this effort will be the consideration of the economic and social implications of providing different levels of environmental flows to achieve certain levels of environmental protection, e.g., preservation, maintenance, enhancement, etc. The role of uncertainty and associated risks due to such factors as insufficient data and unverified modeling in the overall environmental flow will also be considered.

**Environmental Flow Implementation Strategies** - The various options and strategies for implementing environmental flow programs in Texas will be addressed. Existing procedures for protecting environmental flows, such as reservations in new and amended appropriations of surface water and the use of the Water Trust, will be considered. Proposals for new approaches for providing for environmental flows in Texas also will be examined and reviewed, as well as other programs being utilized outside the state.

**Summary Report** - The work undertaken by the SAC and its findings will be summarized in a written report. Each of the elements of the Scope of Work will be addressed in the report, and relevant information will be provided using tables, and charts as appropriate. The report will be provided to the Study Commission in draft form. Following review and comment by the Study Commission, the report will be finalized.

## **ACKNOWLEDGMENTS**

The Science Advisory Committee is grateful for the strong support and assistance it has received throughout the course of its activities and investigations from the staffs of the Texas Commission on Environmental Quality, the Texas Water Development Board, and the Texas Parks and Wildlife Department. Staff members from each of these agencies provided extensive resource documents and materials regarding hydrological and environmental conditions and the environmental flow programs in the state, presented explanations of the roles and responsibilities of the agencies with regard to environmental flows, and assisted with preparation of portions of the draft report. The SAC appreciates the efforts of Ms. Tangela Niemann, Mr. Bruce Moulton, Mr. Todd Chenoweth, Ms. Robin Smith, Mr. Lann Bookout, Ms. Kathy Alexander, Mr. Doyle Mosier, Mr. Herman Settemeyer, Mr. Steve Densmore, Dr. Barney Austin, Dr. Jungii Matsumoto, Dr. David Brock, Dr. Larry McKinney, Ms. Cindy Loeffler, Ms. Colette Barron, Mr. Kevin Mayes, Dr. Randy Moss, and Mr. Dave Buzan. Ms. Carolyn Brittin has been especially helpful coordinating the activities of the SAC, facilitating committee meetings and conferences, and assisting with the organization and production of this SAC report to the Study Commission.

# 1. INTRODUCTION

There appears to be little argument that environmental flows are important and necessary for maintaining the ecological health of the Texas' rivers and streams and its bays and estuaries; the difficult question is: what flow regime is required to assure the state's ecosystems are adequately protected. A flow regime consists of a quantity of water, the seasonal or yearly timing of the occurrence of this water, and the size and frequency of flow events. This question has been addressed by the state's water and environmental agencies for many years—over three decades for the bays and estuaries. Of course, if the ideal flow regime was known for a particular aquatic ecosystem, there would remain the equally important question of how the requirements for environmental flows can be satisfied with the limited supplies of water that are available in many parts of the state while still meeting all other important demands for water.

Given the scientific, social, legal, and philosophical complexities of the issue, it is not surprising that answers to these environmental flow questions have been elusive. The focus of this Science Advisory Committee (SAC) has been on science of environmental flows, with the goal of evaluating the scientific basis for the state's approach with regard to determining appropriate environmental flow recommendations and how the science might be improved to provide the best technical information available so resource managers and policy makers can be confident that decisions are sound and result in sufficient water for both human uses and nature.

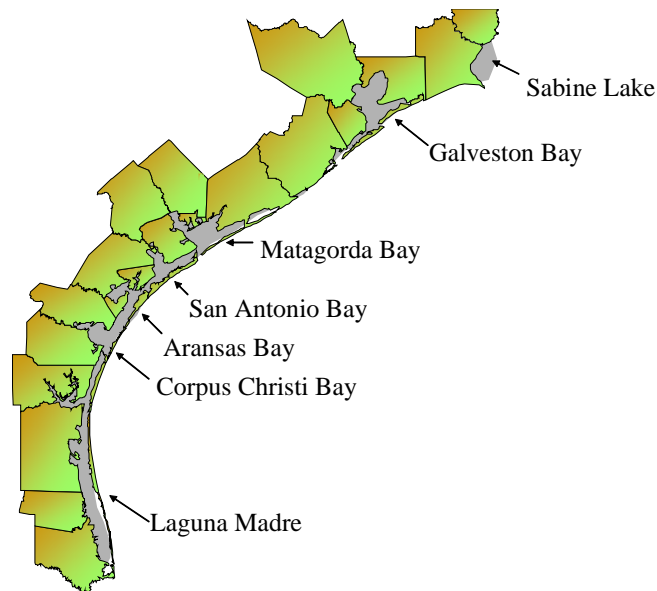
In its consideration of environmental flows, the SAC has focused only on those surface waters in which the movement of water, i.e. the flow, is an essential aspect of the character of the watercourse. There are two broad categories of such watercourses: rivers and estuaries. This report addresses both.

A river or stream is a watercourse in which the flow is confined to a well-defined channel and is derived from rainfall runoff or springflow. In Texas there are over 11,000 named rivers and streams with a total channel length approaching 200,000 miles (Figure 1-1). These streams flow generally downslope to the Gulf of Mexico, and as they do so, they merge and conflow, organizing themselves into the drainage networks of the major river basins, described as "dendritic." With three major exceptions (the Canadian, Red, and Rio Grande), the headwaters and drainage basins of these rivers are entirely or almost entirely contained within the state. Four of the state's principal rivers—the Canadian, Red, Sulfur, and Cypress—flow into adjacent states.



**FIGURE 1-1 TEXAS RIVERS AND STREAMS**

The other principal rivers eventually drain to the Texas coast. It is here that the second category of watercourse is encountered in which flow is essential, the estuary. An estuary is a waterbody in which water draining from the land intermixes with seawater. From the standpoint of flow, the key distinction between a stream and an estuary is that in an estuary is influenced by freshwater flows from upstream and tidal flows from the Gulf. The importance of each source of water is determined not only by the magnitude of its flow, but also by its qualities. There are seven major bays in Texas, each of which is an estuary (Figure 1-2), as well as several minor estuaries not associated with a corresponding bay.



**FIGURE 1-2 MAJOR TEXAS BAYS AND ESTUARIES**

### **1.1 State Environmental Flow Activities**

In Texas, the Texas Commission on Environmental Quality (TCEQ) is responsible for regulating and administering water rights that authorize the use of surface water. When considering applications for new permits to use surface water and applications for certain amendments of existing water rights, the TCEQ must assess the potential impacts of the proposed action on freshwater inflows to the bays and estuaries, existing instream uses, fish and wildlife habitats, and water quality. To the extent practicable when considering all public interests, the TCEQ may include conditions in any permit or permit amendment issued, as necessary, to effectively address environmental effects. Such conditions may include certain specified minimum levels of streamflow that have to be passed downstream before any water can be used (diverted or impounded) for the new appropriation. These bypassed flows are intended to provide protection for downstream aquatic resources.

When assessing the potential impacts of proposed permits or permit amendments on the aquatic environment, the TCEQ considers and utilizes all available information, including input from the Texas Parks and Wildlife Department (TPWD) and the Texas Water Development Board (TWDB). This includes information regarding flow requirements for protecting instream uses in

rivers and streams and estimates of the freshwater inflow needs for bays and estuaries. Such conditions normally apply at a single location on a watercourse in the vicinity of a water right.

The TCEQ prefers to use site-specific data, when available, to establish requirements for environmental flows in rivers and streams. However, in most cases, such site-specific studies have not been undertaken, so the TCEQ relies on statistical desk-top procedures—which for the most part have not been tested and calibrated for Texas riverine conditions—to assess environmental flow needs and to quantify “default” environmental flow targets. If the TCEQ staff have the opportunity to perform a site visit or if an applicant provides site-specific information, the TCEQ may deviate from the default criteria. Factors that may influence this determination include the presence of specific habitat features that are flow-dependent or the presence (or absence) of aquatic organisms (fish or benthic invertebrates) that suggest a different flow regime. Field studies can vary substantially in scope and effort, depending on the issues to be addressed and the time frame available. Given the resources required, studies of this nature are usually limited to large reservoir projects and significant direct diversions, which have the potential for major downstream hydrological effects. Pursuant to Senate Bill 2 (77th Legislature, 2001), the three state agencies now are in the process of implementing a comprehensive data collection and analytical program to establish environmental flow requirements for rivers and streams across the state (referred to as the Texas Instream Flow Studies program), with results from this effort for specific basins and subbasins forthcoming over the next six years.

The state agencies have been engaged in studies of freshwater inflows for the bays and estuaries since the late 1960s. In recent years, most of the analytical work (data analysis and computer modeling) has been undertaken by the TWDB. The overall process employed by the TWDB is referred to as the State Methodology. The TPWD has been engaged in data collection activities, verification of analytical outputs, and making recommendations as to desired levels of freshwater inflow to achieve various management goals for the different estuarine systems along the coast. To date, only one of the regulatory programs in place for addressing the freshwater needs of particular bays and estuaries (Corpus Christi-Nueces Bay) has been based directly on results from the state’s ongoing studies. As new demands for water emerge and new water projects are proposed, it is anticipated that the outputs from the state’s program will play an increasing role. Consideration of the freshwater inflow needs for bays and estuaries is an extremely complex issue involving various hydrologic, biologic, chemical, and physiographic interactions within these systems, and the methods being employed by the state to address these interactions are complex, as well. It is important that the results being produced are not only responsive to the fundamental question of how to provide adequate freshwater inflows to the bays and estuaries, but also that these results are based on sound and rigorous scientific approaches.

## **1.2 Role of Scientific Process**

At the core of the issue of environmental flows is a scientific problem: determining the effects of the movement of water (and everything that implies) on the biological communities of a waterbody. The reliability of this determination is dependent upon the adequacy of the underlying science. It is therefore appropriate to summarize briefly the process by which that science is established and how it is employed to arrive at this determination.

Science has become more methodized than other human enterprises, such as art or politics, and much of its success derives from that methodology. Its twin pillars are observation and

explication. "Pure science" is considered to be limited to these two endeavors only, while "applied science" uses these results to address issues, answer questions, or solve problems of importance in other disciplines or to society as a whole. Engineering, in this philosophical view, is a subset of "applied science," characterized by seeking quantified solutions to specific human socioeconomic needs, such as production of materials, transportation, habitation, protection from the elements, waste disposal, communication, and so forth. Its service is utilitarian, and is generally rather narrowly focused on devices and structures, e.g., machinery, power generation, chemical plants, smelters, ports, roads, pipelines, buildings. Applied science (*a fortiori* engineering) frequently relies on fitting a relation to measurements, thereby quantifying a connection between variables, in order to facilitate solution of the problem at hand, rather than analyzing the fundamental principles.

Of course, the many fields of science, the variety of approaches, and the range of questions addressed, make the reality of scientific method much more complex than the stark, simplified depiction of the preceding paragraph. There are numerous scientific disciplines, with even more numerous specialties, all of which address delimited parts of "reality." Observation encompasses classification and measurement, each of which entails a variety of procedures and techniques, depending upon the subject. Explication can range from identifying associations of observations to the formulation of a complex of hypotheses, referred to as a "theory." Nor are these disjoint and separate activities. Observation of a phenomenon may require theory from another discipline, and the skills of the engineer to develop the technology of measurement. While it is sometimes convenient to characterize scientists as "empiricists" versus "theorists," this is more a matter of degree than strict differentiation. Some disciplines, such as hydraulics or oceanography, require application of the principles from other disciplines (e.g., physics and chemistry), and therefore have much of the character of an applied science.

The interplay between experiment and theory in laboratory physics has become the paradigm of the scientific method. The rule is sought by which one physical variable is influenced or affected by another variable, say the fall speed of an object as affected by the elapsed time from when it was dropped. The first variable (in this example, the fall speed) is the response or predictand, the second (the elapsed time) is the independent variable or predictor. The experiment is a strategy of measurement in which both variables are observed, perhaps over a range of values, while the effects of additional variables (such as atmospheric drag and air density) are eliminated, by being minimized or held constant. A hypothetical rule in the form of a mathematical relation (the "theory") is to be tested, by comparing the predicted value computed from the theory with the value measured in the experiment. If the two agree, the theory is said to be "verified" by the measurement. The mathematical rule is a "model" of the relation between the variables. This rule could be empirical, as a relation fitted to a set of measurements, or theoretical, as an inference from a set of hypotheses.

There are many deep ramifications of this paradigm, which have filled tomes on the philosophy of science, such as the asymmetry between theory verification and falsification, and the meaning of a "crucial" experiment. In the present context, this paradigm is useful to illustrate three important concepts of the scientific method. The first of these is the practice of isolating the effects of a single predictor variable by manipulating the experimental design so that the effects of other variables are eliminated. Such a design is called a "controlled" experiment, and the non-operative variables are said to be controlled. The second concept is the notion of "error," which in scientific parlance refers to a level of uncertainty in a measurement, evidenced by different

values of the measured variable under apparently identical conditions. These differences in measurements are conceived to arise from sloppiness in procedure or calculation, from the operation of additional external factors that are unrecognized and hence not considered in the experimental design, and from the natural imprecision of the measurements. In theory, all of these can be removed by design or improved precision, but in practice there will remain a residual level of random variation that limits the accuracy of the measurement.

The third concept involves the occurrence of "free parameters" in the model, manifested as unknowns in the mathematical relations whose values cannot be established from external (e.g., theoretical) considerations. In the present example, the acceleration of gravity would be such a parameter. Its value has to be established empirically by a single set of paired measurements of predictor (elapsed time) and predictand (fall speed) —or better, by the slope of the best-fit line to several such paired measurements. With this parameter thereby quantified, the model (the relation of fall speed to elapsed time) is said to be "calibrated." Additional, *independent* pairs of measurements would then be needed to verify the model. (Actually, the present simplified example, offered as illustrative, is in fact part of a larger physical theory that affords an independent and external calculation of the acceleration of gravity.)

The problem with the laboratory-physics paradigm of scientific method is that it does not readily extend outside of the laboratory, in that the phenomena of concern may be far more complex than a simple two-variable dependency, and, more importantly, a controlled experiment cannot be set up. This is the case for most of the natural sciences, including meteorology, hydrology, watercourse fluid mechanics, riverine and estuarine chemistry, and aquatic biology—the sciences involved in establishing environmental flows. Observations in the various aquatic sciences (as well as geosciences in general) are logistically difficult and expensive, and tend to be sparse in space and time. There are numerous sources of error, and many variables affect the measurements, usually themselves not monitored, perhaps not even recognized. Since the influence of these variables cannot be eliminated, field measurements are intrinsically *uncontrolled*. There exists a considerable aggregation of techniques for handling such measurements and using them in model validation.

The vastness of scientific problems, whether "pure" or "applied," relative to the capacity of a single individual, entails another central feature of scientific method: It is a *collective* enterprise. While this ensures progress from the shared benefits of the pooled work of many scientists, it also imposes additional requirements on the scientific method. There are two of prime importance: first, scientific work must be given clear and unambiguous documentation; second, scientific work must be capable of *replication*. For theoretical results, "replication" means duplicating the reasoning from premise to conclusion, e.g. mathematical derivations, thereby confirming the validity of those results. For observational results, the experiment should be capable of duplication and the resulting measurements (and associated model relationships) should agree, to within the experimental error.

The principle of replication of study results by capable scientists is also referred to, rather imprecisely, as "peer review." Over its long history, the enterprise of science as a collective effort in providing new theories and observations, and subjecting these to peer review through replication, has resulted in advances in information and understanding about the natural world. This enterprise is usually incremental ("normal science") but is occasionally discontinuous ("revolution"). Corollarily, scientific progress is convergent, and it is *self-correcting*. Scientists

are not immune to the defects of the human species, and many false assertions have been advanced, arising from simple mistakes, from bias due to conviction or misconception or wishful thinking (aided, perhaps by vested interests), to unmitigated fraud. With the accumulation of information and the unrelenting requirement of replication, false assertions are eventually brought to light.

In the natural sciences, and in particular in the aquatic sciences, replication is strictly impossible, because a field measurement cannot be duplicated. It can be *repeated* at a later time, perhaps, but the complete combination of conditions under which the original measurement was made never recur. Moreover, many field programs in aquatic sciences involve a major expenditure in equipment and personnel, which is prohibitive for an independent scientist to command merely to replicate field measurements—even if the same external conditions could be approximated. The process of replication in natural sciences is replaced by one of *corroboration*, which focuses on the measurement protocols, handling of data, repetition of analyses, and evaluation of statistical variance in the data—all assuming that the basic readings of instruments are reported exactly. Such corroboration is further strengthened by a weight of evidence emerging from later measurement programs that yield consistent conclusions. Corroboration is typically beyond the resources of individuals, who are limited to mere perusal of publications, and requires a concerted and systematic effort by groups of scientists, frequently at a level of effort that rivals the original work. Many of the published results in aquatic sciences are corroborated only by weight of evidence. (This situation is not peculiar to natural sciences. Clinical studies in medicine, for example, cannot be replicated, for many of the same reasons, and can at most be corroborated by other scientists evaluating procedures and analyses, assuming that the basic data are recorded correctly.)

That science is a collective enterprise also necessitates standards of conduct: good manners, as it were. These include courtesy sharing of results, proper citation and acknowledgment of priority in a discovery or observation, and pre-publication review of published work to achieve some level of winnowing of illegitimate or flawed results. This last activity is, unfortunately, also referred to as "peer review," but it is much more superficial than the rigor of peer-review replication that is essential to the scientific method. The society of scientists, like the larger society of humans, is made up of specialists, most of whom do not routinely engage in the entirety of the scientific method, but focus on narrow tasks, such as collection of highly specialized information, or in the performance of increasingly precise measurements, or in the mathematical development of an aspect of a theory. Many scientists, as a consequence of their specialization, may not even be appreciative of the nuances of the methodology, which occasionally has led to gaffes.

In the application of scientific results to societal issues, the nature of scientific progress as an incremental convergent process, combined with its intrinsic uncertainty ("error" in the above summary) should be noted. This means that at any point in time the scientific answer to a practical question, notably the determination of flows necessary to sustain an aquatic ecosystem, is provisional and approximate. This does not mean that the answer is useless. On the contrary, the entirety of applied science, including the disciplines of engineering, is founded upon such provisional results and, hopefully, is devoid of "science with an agenda." It does mean that in addition to the answer, the confidence in that answer must be appraised—including not only the probable range of error, but also the degree of corroboration that the underlying science has received. There should also always be a continual questioning of the basic assumptions from



which interpretations, “answers” and model outputs are derived and corrections made where justified. Natural systems provide ample room for iterative process interpretations, where we make scientific judgments based on best-available information, but continue research programs to refine those interpretations. Generalizing and transferring research about natural systems in one area to another also is difficult due to the uniqueness and complexity of individual ecosystems. So with regard to environmental flows, continuing research will be necessary to more accurately assess ecosystem impacts and guide management needs.

### **1.3 Goals for Environmental Flows**

The principal goal of providing environmental flows is to assure that sufficient quantities of water, reflecting seasonal and yearly fluctuations, as well as the frequency, timing, and volume of high-flow events, are made available to adequately protect the state’s aquatic ecosystems. As with any effort to characterize an ecosystem—whether it is a stream, river, lake, reservoir or estuary—researchers and resource managers face the daunting task of selecting appropriate measurable indicator parameters and understanding the interaction of natural and human-induced events and their impacts on the parameters. Describing or defining “ecological health” or “ecological integrity” or a “sound ecological environment” for purposes of managing ecological resources and providing appropriate levels of environmental flows is not an easy task. To determine the “soundness” of the ecological environment, indicators must: (1) be identified; and (2) fall within an acceptable “healthy” range. Practical difficulties include the lack of simple indicators of ecological health and a frequent insufficiency of data to determine the acceptable ranges of ecological health. The definition of a sound ecological environment is further compounded because it depends on definitions of other terms, such as ecological function, integrity, and sustainability. An alternative, perhaps more fundamental, indicator of ecological health is the sustainability of goods and services provided to humans by the ecosystem over multiple generations.

Because human values often provide the basis for defining health, more often than not, it is the individual interpretations of ecosystem viability that exhibit common general characteristics, but may vary when it comes to detailed descriptors. Costanza (1992) defined a healthy ecosystem “...as being ‘stable and sustainable’; maintaining its organization and autonomy over time and its resilience to stress.” In an article titled “Assessing Ecosystem Health”, Rapport, Costanza, and McMichael (1998) list indicators of ecosystem health to include “vigor, organization, and resilience.” Similarly, the Texas bay and estuary studies have considered characteristics of survival, growth, and reproduction of key estuarine species as measures of ecosystem vitality. Now, the Texas Instream Flow Studies program proposes to determine flow conditions necessary to support a sound ecological environment in the river basins of Texas. The goals of the program are to conserve biodiversity and maintain biological integrity.

While defining and measuring the indicators of ecosystem health is challenging, assessing the effects caused by human pressures versus natural occurrences represents an additional layer of complexity. Future management of water resources must be able to distinguish between human and natural events in order to design effective strategies that are able to target specific ecosystem health issues and causal factors.

For regulatory purposes, it is often the directive from a governmental entity that defines the goals that are to be met, relative to the protection and maintenance of ecological resources. This

process, in turn, serves to define how ecological health is to be achieved. In Texas, it is the language included in legislation passed by the Texas Legislature that has provided direction to the state agencies with regard to how the ecological resources of the state are to be protected and maintained. It is this language that has been interpreted by the state agencies to define how and at what levels environmental flows are to be provided for. Following are discussions of the legislative history regarding provisions for environmental flows for rivers and streams and bays and estuaries.

### **1.3.1 Rivers and Streams**

In 2001, the Texas Legislature enacted Senate Bill 2, which in part, amended Section 16.059 of the Texas Water Code to provide for a data collection program and the assessment of instream flows for Texas riverine systems. The TWDB, TPWD, and TCEQ were directed to "...conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state's rivers and streams necessary to support a sound ecological environment." Agency staff, in developing the programmatic work plan to implement the requirements of the legislation, which now is referred to as the "Texas Instream Flow Studies" program, have provided a more detailed interpretation of streamflow conditions for Texas rivers and streams. For purposes of the work plan, instream flows are described "...as the flow regime adequate to maintain an ecologically sound environment in streams and rivers including riparian and floodplain features (considering hydrology, biology, geomorphology, water quality, and connectivity) and necessary for maintaining the diversity and productivity of ecologically characteristic fish and wildlife and the living resources on which they depend. Instream flows may also be defined as those flows needed to support economically and aesthetically important activities such as water-oriented recreation and navigation."

The three agencies have stated that the goal of the Texas Instream Flow Studies program should be "...to determine an appropriate flow regime (quantity and timing of water in a stream or river) that conserves fish and wildlife resources while providing sustained benefits for other human uses of water resources." In addition, the proposed instream flow studies are to take a holistic approach to assessing the needs of the rivers and streams, whereas the freshwater inflow studies have concentrated on inflow needs for a limited number of target species.

### **1.3.2 Bays and Estuaries**

In 1975, the 64<sup>th</sup> Texas Legislature enacted Senate Bill 137, which called for the TWDB to conduct studies of the effects of freshwater inflows on the bays and estuaries of Texas, including "...the development of methods for providing and maintaining the ecological environment thereof suitable to their living marine resources." In the 69<sup>th</sup> Texas Legislative Session and subsequent sessions, amendments were added to the Texas Water Code, which directed the TWDB and TPWD and other cooperating governmental agencies to "...conduct studies and analyses to determine bay conditions necessary to support a sound ecological environment". The Texas Legislature also added Texas Water Code §11.1491, relating to the evaluation of bays and estuaries data, calling for the TPWD and the Texas Natural Resource Conservation Commission (now the TCEQ) to review the aforementioned studies, and "...to determine inflow conditions necessary for the bays and estuaries..."

To meet the directives of the Legislature, the cooperating agencies had to interpret the intent of the legislation with regard to the phrase “sound ecological environment” because the legislation did not contain a definition. The *Freshwater Inflows to Texas Bays and Estuaries* report (Longley, 1994) offers two definitions, one termed conceptual and the other operational. From a conceptual standpoint, a sound ecological environment occurs “...when the typical physical, chemical, and biological parameters that are measured—including the characteristic biological communities—fall within the range of values that historically occurred before humans interfered with natural processes (e.g., by constructing waterways, introducing pollutants, and altering freshwater inflows).” The second (operational) definition describes a sound ecological environment as: “...having densities of animal and plants not significantly different from the historical patterns of abundance or composition.” The Longley report also notes another characteristic associated with a sound ecological environment relates to maintaining the production of fishery species in a bay or estuarine system.

Included in the 1985 amendments to §11.147 of the Texas Water Code was a definition for “beneficial inflows.” The definition stated, that beneficial inflows means “a salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is 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.” While the emphasis was on those species that contribute to the economy of the coastal region through commercial and recreational benefits, the state agencies were also charged with assessing estuarine life as a requisite for maintaining viable populations of commercial and sport species. Nonetheless, from the standpoint of maintaining a sound ecological environment, the emphasis on commercial and sport species results in an extremely narrow focus that omits many other important elements of a healthy estuary.

What are the indicators of a healthy estuary in terms of altered freshwater inflows and ecological sustainability? Because habitats are so important to the structure and function of estuaries and are at risk when inflow regimes are altered, measures of habitat productivity, extent, and persistence over time are likely the best indicators of ecosystem sustainability. Habitats are important because they are the best indicators of ecological integrity and thus key to sustainability of the ecosystem.

The best indicators of sustainability will be measures of ecological integrity, in particular diversity and species composition and biomass of characteristic estuarine species that are sensitive to changes in salinity patterns. The biomass, density within the habitat, and areal extent of a habitat of all species is particularly important. This is especially true for many vegetated habitats, such as freshwater or saltwater marshes, seagrass habitats, or oyster reefs. All of these are especially sensitive to changes in inflow regimes. In areas without extensive vegetated or reef habitats, soft-bottom benthic habitat characteristics will be important (Montagna and Kalke 1992). Benthic mollusks, especially bivalves, are especially good indicators of inflow effects (Montagna and Kalke 1995).

#### **1.4 Uncertainty and Risk**

Uncertainty arises from a variety of sources including lack of basic understanding regarding the issue in question (environmental or otherwise), lack of relevant data to adequately analyze the

issue, measurement error, and the extent to which scientific models do not fully capture the complexity of the processes involved. A common pitfall is to assume that the most scientifically rigorous methodologies minimize uncertainty. While such scientific approaches often provide means to estimate uncertainty that arises from incomplete understanding of natural systems and errors in measurement and characterization of these same systems, such approaches require the necessary commitments of time and resources in order to achieve meaningful results. Without these commitments, these state-of-the-arts methodologies may only provide a guise that obfuscates uncertainty.

Risk is a type of uncertainty that involves, by definition, an “exposure to a chance of injury or loss” (Random House, 1997). For the issue of environmental flows, the “injury or loss” is to ecological health if recommended environmental flows are established too low or are not met, and conversely, to human consumption of water if these flows are established too high. To fully weigh various risks, it is necessary to understand both the extent of injury or loss, and the probability of occurrence, in concrete terms. The probability of occurrence, of these undesirable outcomes can be a direct result of the previously discussed errors inherent in any scientific approach and is proportional to the magnitude of the uncertainty. Hence, the uncertainty involved in the scientific approach results in risk that an incorrect answer is determined for environmental flows, and the greater the uncertainty, commensurately, the greater the risk.

Quantification of uncertainty and communication of associated risk should be paramount in the recommendation of environmental flows to decision makers and could include a range of responses. The processes to determine environmental flows in Texas can be structured to allow better quantification and communication of uncertainty and risk. However, in the broader aspects of decision making, science serves only as input. While science can often quantify the extent of uncertainty, and the probability and magnitude of injury or loss, in many cases significant and unquantified uncertainty can remain. Moreover, science can do little to help decision makers weigh low probability-high injury and high probability-low injury cases that may exhibit similar risk.

## **2. PHYSICAL SETTING**

The fundamental notion underlying environmental flows is the movement of water. This is most directly measured by the velocity of a particle of water (called "current"), which has units of speed, e.g., feet per second, miles per hour, meters per second. We do not perceive water as individual particles but rather as a volume, so it is more useful to measure water movement as a time rate of volume. This is what is meant by "flow." It has dimensions of volume per unit time, e.g. cubic feet per second, gallons per day, acre-feet per year. The name may be further modified to suggest the source or character of the flow, such as inflow, outflow, surface flow, subsurface flow, open-channel flow, and pipe flow. In the present context, "streamflow" refers to flow in a river or stream channel. This is by far the most important type of environmental flow, and the only one considered in this report. This chapter summarizes the two aspects of streamflow that are important in addressing environmental flows in Texas: (1) the sources of streamflow, and how they vary in space and time across the state; and (2) the roles of streamflow in the two types of watercourses considered, the stream channel and the estuary.

### **2.1 Hydrology of Texas**

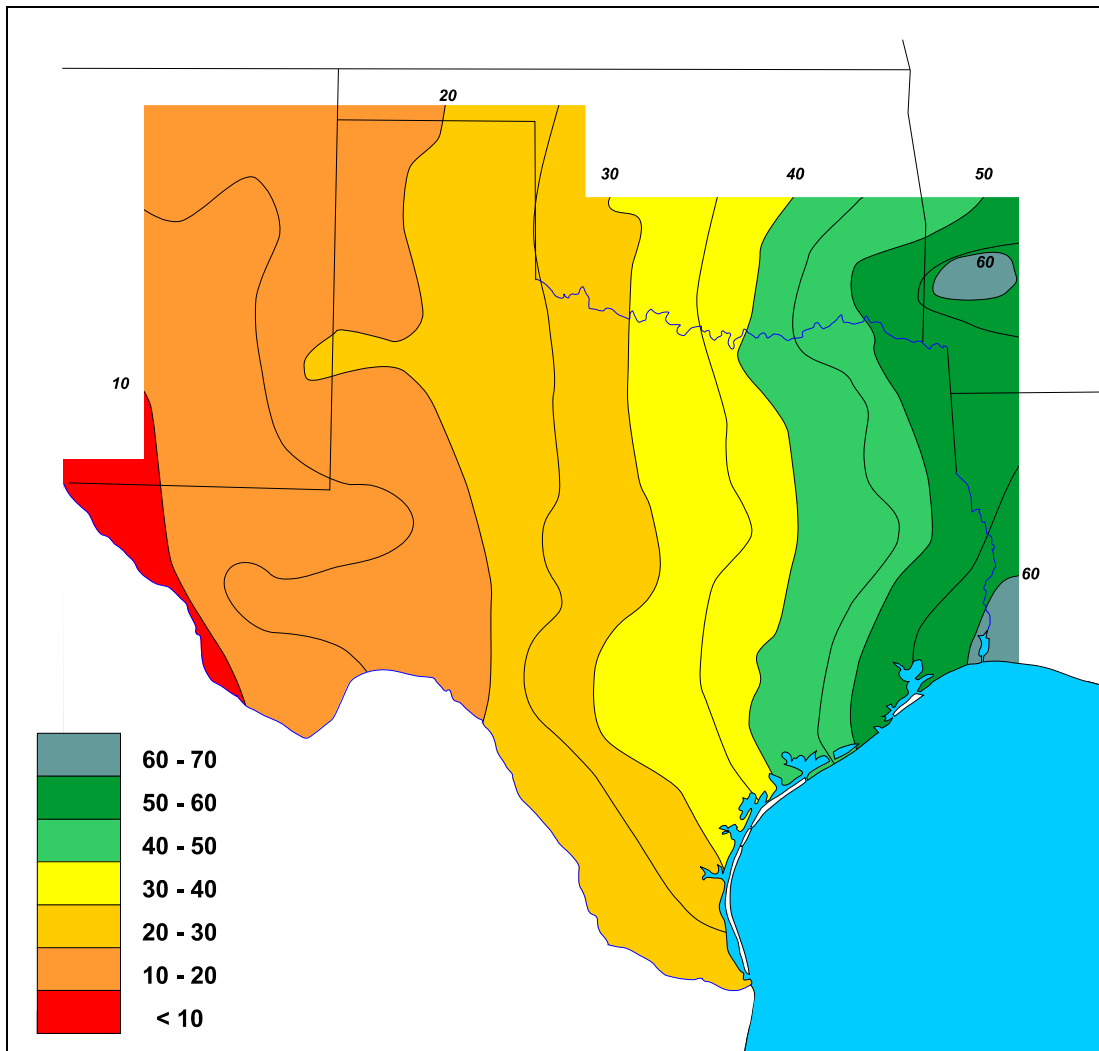
#### **2.1.1 Climate Patterns**

Texas is a state of climatic diversity. Partly, this is due to the size of the state, encompassing an area of 267,000 square miles, and partly to its topography, ranging from sea level to nearly 8,800 feet over its spread of 13° in longitude (about 770 miles east to west) and 11° in latitude (about 730 miles north to south). Mainly, however, this climatic diversity is due to the position of Texas on the North American continent.

With distance southward along a central north-south axis, the width of the continent markedly decreases, so that two of the three main determinants of North American climate—namely the Rocky Mountain cordillera to the west and the ocean to the east—are pinched together. Westerly winds flowing onto the American continent from the Pacific are forced up and over the Rocky Mountains, losing their moisture in the process and descending to the Great Plains as warm, dry air: the arid climate created in the lee of the Rockies is the "rainshadow." East of the Rockies, the Gulf of Mexico is the principal source of atmospheric moisture. Flowing northward from the Gulf, this moisture is entrained into the westerlies, creating a west-to-east gradient in humidity, increasing from the Great Plains to the Atlantic. These two processes—the rainshadow of the Rockies and the moisture influx from the Gulf—are compressed across the west-to-east extent of Texas. The third main determinant of North American climate is the southward transition from midlatitude westerlies to tropical easterly winds, concentrated in the latitudes around 30°, approximately central in the range of latitudes of Texas. This means that across the north-to-south extent of Texas there is a steep gradient from the climate of the westerlies, with its traveling synoptic disturbances, to the climate of the Trade Winds, with its subsiding airmasses and high solar radiation.

As a consequence of these climatic factors, the distributions of average temperature and average precipitation in Texas are very different. Temperature is mainly governed by the southward increase in solar radiation, in combination with the declining effect of synoptic disturbances

entering the state from the north, and the mean isotherms (“contours of equal temperature”) consequently align with parallels of latitude. In contrast, the mean isohyets (“contours of equal precipitation”) tend to align with meridians of longitude, as exemplified in Figure 2–1, due to the rainshadow of the Rockies. This east-to-west decrease in precipitation is one of the major features of Texas climate. There is a six- to seven-fold increase in precipitation (depending upon the averaging period) from the high desert of the Trans-Pecos region to the humid, eastern forest region of East Texas.



**FIGURE 2-1 LONG-PERIOD 1949–2002 AVERAGE ANNUAL RAINFALL IN TEXAS (isohyets in inches per year)**

The climate of Texas is highly variable in time as well as space. Temperatures exhibit their highest range and greatest variability in the winter, when the state is under the alternating influence of cold front passages, associated with synoptic disturbances in the westerlies, and inflows of warm, moist air from the Gulf. The season of maximal rainfall in Texas varies from winter in the eastern part of the state to summer in the High Plains and Trans-Pecos regions. Much of Texas experiences seasonal maxima in both spring and fall, so that the annual pattern of

precipitation is bimodal (“double peaks”). These seasonal maxima arise from the interaction between dry, cool airmasses thrust into the state from the north by synoptic-scale disturbances, and the inflow of warm, moist, unstable air from the Gulf, this interaction being greatest during the spring and fall seasons.

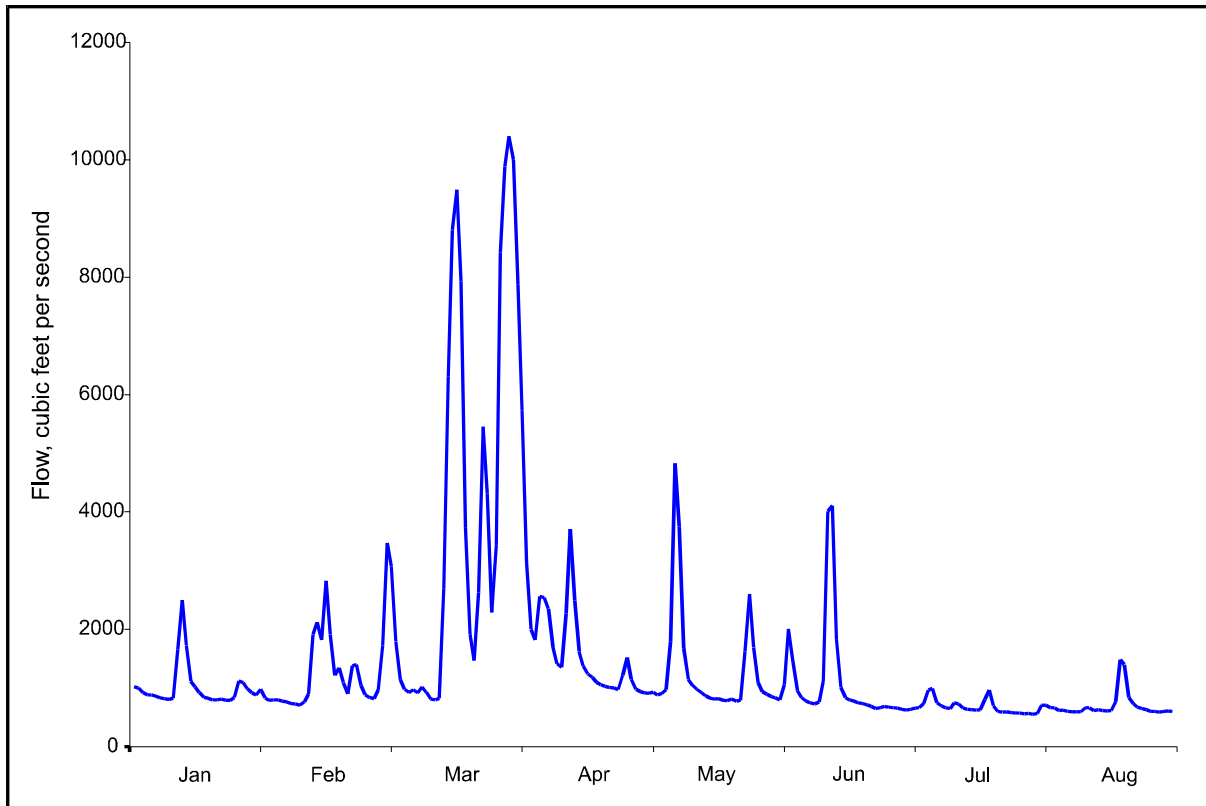
Of primary importance to any consideration of water issues in Texas is the extreme variability in rainfall, more than simply its increase or decrease with the seasons of the year. In Texas, precipitation is almost entirely liquid, and originates predominantly from thunderstorms. Because of this convective origin, rainfall delivery is concentrated in short bursts. The triggering mechanisms for such storms range from solar heating on the small scale to vertical displacement of airmasses on the synoptic scale. It is the seasonal variations of these triggering mechanisms that are responsible for the dramatic variations in rainfall over the year.

Rainfall is the primary source of water in the streams and rivers of Texas. It enters these watercourses by two pathways. First, and most important, is runoff from the land surface, which moves into drainage ways by gravity flow (hence its name). This is the surplus water left after absorption of rainfall into the watershed surface. The watershed absorption is the combined processes of interception and infiltration. This absorbed water is evaporated directly back to the atmosphere, taken up by plants and transpired back to the atmosphere, retained in the soil layers, or percolated into water-bearing rock formations called aquifers. In the latter two processes—storage in soil or aquifer—water moves at a much slower rate than at the surface, but some eventually finds its way into tributaries that have cut through the soil or rock layers. This is the second pathway by which water enters the streams and rivers, e.g., springs.

Runoff is driven by precipitation at the surface and by the capacity of the watershed to absorb rainfall. Because of the east-to-west decrease in rainfall, there is an associated east-to-west decline in the potential for runoff. In addition, however, the increasing aridity with distance westward implies a greater capacity of the watershed to absorb rainfall. The resulting runoff in fact declines from east to west even more rapidly than rainfall. In East Texas as much as 25% of the rainfall on the surface appears as runoff into the stream system, but with distance westward, this drops by an order of magnitude, i.e. to less than 2% in the western sections of the state (west of about longitude 100°W, i.e., west of north-south line through Abilene).

### **2.1.2 Droughts and Floods**

Inspection of a record of streamflow in any of Texas’ rivers and streams discloses a series of spikes of flow superposed on a much lower quasi-steady flow. An example of eight months of daily flow measurements on the Trinity River is shown in Figure 2-2. These spikes are the runoff events resulting from individual storm systems, referred to as “storm hydrographs.” The occurrence of these storm systems is controlled by large-scale patterns of atmospheric winds and pressure. As noted above, for much of Texas, mainly the central segment of the state, the interaction of disturbances in the westerlies with moisture influx from the Gulf of Mexico is most intense in spring and fall, producing seasonal maxima in streamflow during these seasons. In the spring months on the Trinity (Figure 2-2), these interactions are evidenced by streamflow spikes of higher magnitude and longer duration, occurring more frequently in time and space (“clustering”), thereby resulting in the seasonal maximum in flow.



**FIGURE 2-2 MEASURED DAILY FLOWS DURING JAN–AUG OF 1984 ON THE TRINITY RIVER AT TRINIDAD**

All of the water transfer processes have physical limits: runoff results when the absorptive capacity of the watershed is exceeded, and when the rate of runoff exceeds the flow capacity of the drainage or stream channels, the excess water remains or encroaches upon the landscape—the condition of flooding. The fact that thunderstorms are the predominant source of rainfall in Texas means that rainfall delivery is concentrated in both space and time, so that flooding is common. A major flood occurs nearly every year somewhere in Texas. Precipitation enhancements by synoptic-scale lifting associated with westerly disturbances traversing the state from the north or by tropical depressions entering the state from the Gulf of Mexico are the most common causes of flooding. During September 8–10, 1921, such a tropical system led to record floods in an area of south-central Texas from San Antonio to just north of Temple. Rainfall rates in some localized areas approached 38 inches in 24 hours. The intense rainfall in September and October of 1967 associated with a tropical storm (the remnants of Hurricane Beulah) caused flooding from the Rio Grande to the Guadalupe. In October 1994, a complex interaction of a fall frontal passage with high Gulf moisture and the remnants of a Pacific tropical storm resulted in record flooding from the Lavaca to the Sabine. The 5-day cumulative flow in the San Jacinto River was estimated to have a 10,000-year return period. Intense scouring of sediments along the San Jacinto ruptured several pipelines, and the nation woke to television videos of petroleum fires on the surface of Galveston Bay.

The much lower flow on which flood spikes are superposed is referred to as “base flow.” Base flow is fed mainly by water contributions from the soil layers and aquifers and by return flows from human activities such as irrigation and wastewater discharge. The most spectacular natural



base-flow source is springflow. Many of Texas' rivers (especially in the Colorado, Guadalupe, San Antonio, Nueces, and Rio Grande basins) have base flow supported by springs, though pumping of groundwater in the past century has led to reduction or elimination of hundreds of such springs statewide. The natural sources of base flow are recharged by infiltration of rainfall, and as time increases between storm events, or the magnitude of these events decreases, or both, base flow slowly diminishes. In terms of frequency of occurrence, base-flow conditions compared to storm hydrographs are by far the more common, but there can be a considerable range in the magnitude of base flow depending upon the frequency and intensity of storms. Everywhere in Texas there is a "low-flow season," typically—but not everywhere—in the summer. These low-flow seasons are often more prone to degraded water quality because of the limited dilution of pollutants, a condition exacerbated by high temperatures. For a number of streams and rivers in Texas, the major contribution to base flow is now discharges of treated wastewater ("return flows").

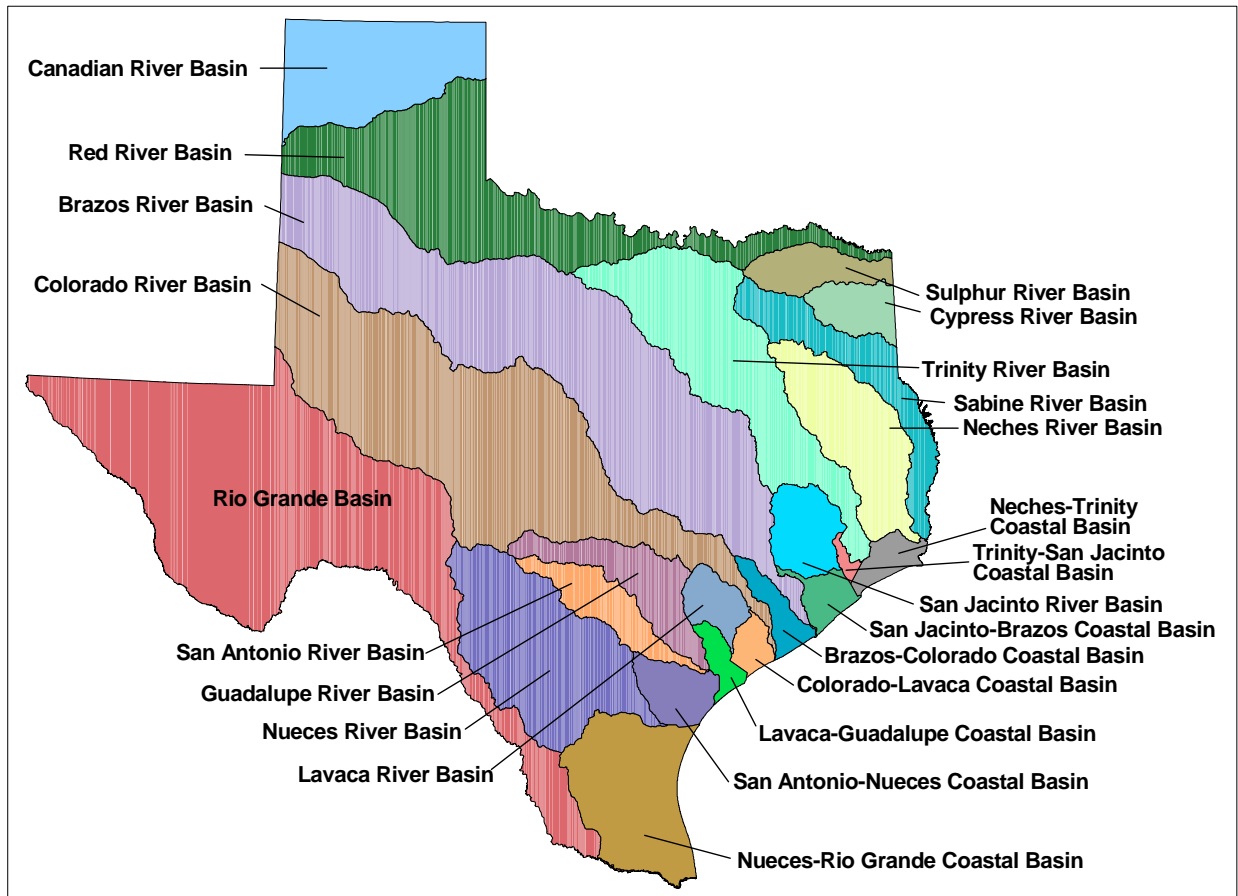
Runoff, it should be observed, is the difference between two large, nearly equal numbers: rainfall and landscape absorption. Relatively minor changes in either (or both) can entail major changes in their difference, and therefore in the flows of Texas streams. (Moreover, of the elements of the hydrological cycle in Texas, it is of these two that our scientific understanding is most deficient.) Long period vacillations in large-scale atmospheric patterns (notably the wave-like features of the westerly winds) enhance or suppress the occurrence of thunderstorms, which in turn, controls the delivery of rainfall at the surface. A sustained period of suppressed storm activity produces the condition of drought, which is recorded as having plagued Texas from the early days of European settlement.

In Texas, drought reoccurs on a relatively regular basis. The need for reliable water supplies during droughts has led to the state's extensive system of reservoirs and delivery systems. Major droughts have occurred somewhere in Texas during every decade of the Twentieth Century. Some of these were statewide but differed in duration and intensity. Among these are the droughts of 1932–34 (the "Dust Bowl"), 1938–40, 1947–48, 1950–57, and 1960–67. Local regions were harder hit. For example, the Llano River near Junction had a continuous drought from 1938 through 1948, bridging the statewide droughts of 1938–40 and 1947–48. Similarly, the Clear Fork of the Brazos suffered continuous streamflow deficits from 1947 through 1957, bridging the 1947–48 and 1950–57 droughts. The Frio River near Darby recorded a streamflow deficit for the 16-year period from 1941 through 1957. The drought of the 1950s is regarded as the worst Texas drought in the period of hydrological data collection (starting in the late Nineteenth Century). For most of the river basins in Texas, this is the "drought of record," and forms the basis for the determination of project yields in water management planning. The omnipresent and essentially unpredictable vacillation between drought and flood dramatically illustrates why successful water management in Texas must consider variations in hydrological conditions, not simply average conditions.

### **2.1.3 Streamflow Variations**

Geographically, the topography of Texas produces networks of stream and river systems draining to a common outlet, thus defining the river basins of the state (Figure 2-3). While many of these basins largely originate within the state and debouch at the Texas coast into its bays and estuaries, there are notable exceptions, such as the drainages of the Red, Canadian, and Sulphur Rivers, that span the adjacent states. The alignment of the major Texas river basins is generally

along a northwest to southeast axis; thus, the streamflows in these basins hydrologically respond to the east to west pattern of decreasing rainfall and runoff, and the north to south pattern of increasing insolation (exposure to the sun's rays) and decreasing humidity. A basic appreciation of the state's large-scale hydrology may be gained from superimposing these rainfall and insolation patterns on the basins.



**FIGURE 2-3 TEXAS RIVER BASINS**

For purposes of this report, the spatial and temporal variations in streamflow in the state are illustrated, using results from the Water Availability Models (WAMs) developed for each of the basins by the TCEQ, pursuant to the requirements of Senate Bill 1 (75<sup>th</sup> Legislature, 1997) and House Bill 76 (77<sup>th</sup> Legislature, 1999). The development and application of these models are discussed further in Section 3.3 of the following chapter. Each of these WAMs is a water-volume computer simulation model that employs on the order of 50 years of historical monthly streamflows as measured at gages within each basin, naturalized to remove the historical influences of man<sup>1</sup>, to evaluate the available supply of surface water for each of the individual

<sup>1</sup> It should be noted that "naturalized flows" are not "dehumanized flows." "Naturalized flows" reflect the removal of the effects of human "plumbing" from historical flows (historical diversions, return flows, and reservoir storage and evaporation), but not all of the effects of human development. These flows are not representative of conditions that existed prior to colonization in Texas, as "naturalized flows" do not remove the effects of widespread agricultural and ranching activities, nor of urbanization, which entailed major changes in land use and land cover within the basins and consequently, modified watershed runoff characteristics.

water rights in each basin, taking into account appropriate priorities for water allocation during periods of shortage<sup>2</sup>. An advantage of using the WAM results over those from an analysis restricted to actual hydrological measurements is the ability to examine the individual effects of human activities under various scenarios and assumptions.

The monthly streamflows from two scenarios associated with WAM operations are presented here:

- “Naturalized Flows”: the flows resulting from the adjustment (“naturalization”) of historical measured flows to remove the effects of historical diversions, return flows, and reservoir storage and evaporation losses, with such naturalized flows being used as the basic inputs to all WAM simulations.
- “Current-Conditions Flows”: the flows simulated with the WAM assuming that all permitted diversions and return flows are operated in accordance with the actual maximal water use in the last 10 years and that all permitted reservoirs have stage-area-storage characteristics corresponding to year-2000 conditions (WAM Run 8).

Changes induced by man that result from increasing population, construction of reservoirs, etc., are a continuously varying component of the historical data record from stream gages, and greatly complicate the use of actual long-term measured streamflows for purposes of water availability analyses and planning. The value of computer generated streamflows is the ability to estimate hydrology under fixed conditions, as well as the ability to estimate streamflows at points in the basin where gages do not exist. Hence, the comparison of sets of flows for the different basins in Texas, as simulated with or as used in the WAMs, is a useful exercise.

Table 2-1 tabulates average monthly flows on the principal rivers in Texas under the "naturalized" scenario, and Table 2-2 shows the same monthly flows for the "current conditions" scenario. Three points on the mainstem of each river have been selected for display: the USGS gage location farthest inland on the river (Upper), a gage location approximately midway down the river (Midbasin), and the outlet of the river from the state (Outlet), which for most rivers is the mouth at the coast (Mouth). These tables clearly display the increase in flow with distance down the mainstem of each river, which is the combined result of the cumulated flow moving down the drainage network of the basins and the increase in runoff with position eastward in the state. The diminishment of flow with distance to the west and south is also evidenced. The typical seasonality of flows and its variation from basin to basin should be noted. The monthly maximum flow is indicated by boldface in both tables.

The most important aspect of the data in these Tables 2-1 and 2-2, however, is the effects of the human "plumbing" in each river basin on streamflow, which can be appraised by comparing the equivalent entries in each table. Further, the monthly differences between naturalized and current-conditions flows reflect seasonality in water demand. These differences are perhaps most apparent for the mouth of the Colorado location, where seasonal agricultural demands greatly

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<sup>2</sup> The Prior Appropriation Doctrine, i.e., “first in time, first in right,” is applied in all basins except the Middle and Lower Rio Grande subbasins, which are subject to the class-based (“type of use”) system of water rights administration established by the Courts.

**TABLE 2-1 NATURALIZED MEDIAN MONTHLY FLOWS**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(1,000s of Acre-Feet)												
Red River												
Upper	1	1	1	1	8	<b>10</b>	2	1	3	2	2	1
Midbasin	87	158	228	231	<b>520</b>	393	136	66	166	133	83	82
Outlet*	405	594	732	801	<b>1409</b>	837	329	148	304	424	299	313
Sulphur River												
Upper	12	20	26	21	<b>28</b>	16	2	0	1	3	8	18
Midbasin	46	69	85	62	<b>100</b>	43	9	1	4	8	29	59
Outlet*	150	212	233	231	<b>286</b>	93	17	6	11	21	81	150
Sabine River												
Upper	78	117	131	121	<b>154</b>	55	16	6	11	14	35	80
Midbasin	198	310	<b>348</b>	266	325	163	49	18	32	35	82	205
Mouth	728	841	<b>953</b>	684	631	421	195	91	90	114	188	505
Neches River												
Upper	78	100	102	84	<b>113</b>	48	13	6	7	13	32	49
Midbasin	400	508	<b>517</b>	421	506	197	87	40	38	48	101	295
Mouth	624	<b>806</b>	747	630	680	307	141	73	74	76	160	445
Trinity River												
Upper	57	57	73	110	<b>187</b>	117	22	13	24	24	26	32
Midbasin	195	266	330	299	<b>542</b>	279	84	32	46	96	100	167
Mouth	366	543	476	561	<b>849</b>	498	192	59	101	144	224	385
Brazos River												
Upper	7	10	13	22	<b>80</b>	64	23	15	30	30	14	9
Midbasin	52	86	98	132	<b>310</b>	194	71	42	62	84	53	62
Mouth	231	350	299	359	<b>821</b>	516	226	157	170	209	175	256
Colorado River												
Upper	11	13	13	21	<b>53</b>	34	15	11	27	19	11	11
Midbasin	27	30	35	47	<b>111</b>	82	31	25	42	41	26	26
Mouth	113	128	117	198	<b>381</b>	235	121	95	167	141	109	116
Guadalupe River												
Upper	7	7	8	8	<b>10</b>	9	6	4	6	7	7	7
Midbasin	16	15	19	21	<b>28</b>	21	12	9	14	15	12	14
San Antonio												
Upper	6	5	6	6	<b>10</b>	8	5	3	5	7	5	6
Midbasin	16	15	16	16	<b>22</b>	19	12	10	14	15	13	14
Guadalupe + San Antonio Rivers												
Mouth	93	104	96	95	<b>163</b>	145	83	67	88	97	89	89
Nueces River												
Upper	2	2	2	4	<b>11</b>	9	2	3	5	8	2	2
Midbasin	6	6	7	9	<b>43</b>	<b>43</b>	13	13	19	20	9	5
Mouth	7	7	7	10	<b>42</b>	<b>44</b>	17	16	35	25	9	5
Rio Grande												
Upper	9	7	42	40	44	56	<b>69</b>	66	50	26	16	14
Midbasin	129	124	136	138	165	194	283	360	<b>355</b>	227	129	124
Mouth	173	182	184	200	356	369	309	443	<b>548</b>	410	183	158

\*Outlet = Noncoastal outlet from state.

**TABLE 2-2 CURRENT-CONDITIONS (WAM RUN 8) MEDIAN MONTHLY FLOWS**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(1,000s of Acre-Feet)												
Red River												
Upper	1	1	1	1	8	<b>10</b>	2	1	3	2	1	1
Midbasin	76	138	203	217	<b>466</b>	330	83	16	150	126	77	78
Outlet*	398	573	705	773	<b>1350</b>	758	290	103	261	402	296	300
Sulphur River												
Upper	12	20	<b>29</b>	19	<b>29</b>	11	1	0	0	0	1	15
Midbasin	42	64	82	63	<b>101</b>	40	7	1	3	5	20	46
Outlet*	153	202	224	157	<b>251</b>	68	0	0	16	25	94	149
Sabine River												
Upper	51	87	80	92	<b>120</b>	37	8	3	3	6	15	45
Midbasin	155	254	<b>327</b>	219	261	137	35	12	17	27	59	165
Mouth	712	810	<b>918</b>	643	591	324	120	66	62	72	169	469
Neches River												
Upper	72	98	97	87	<b>106</b>	43	9	4	4	7	21	40
Midbasin	416	493	500	436	<b>508</b>	187	49	29	20	18	82	256
Mouth	602	<b>782</b>	723	577	621	241	53	9	17	31	139	428
Trinity River												
Upper	43	40	55	54	<b>108</b>	64	32	36	44	37	37	36
Midbasin	151	169	197	226	<b>405</b>	229	97	78	88	88	107	131
Mouth	297	438	364	358	<b>703</b>	360	82	9	49	86	192	315
Brazos River												
Upper	2	2	1	3	<b>57</b>	33	1	0	10	7	4	2
Midbasin	27	60	68	91	<b>262</b>	144	29	24	28	39	27	40
Mouth	179	260	177	242	<b>693</b>	333	78	30	72	86	111	167
Colorado River												
Upper	3	3	6	7	20	<b>21</b>	9	8	12	7	3	2
Midbasin	14	13	33	29	61	<b>82</b>	75	58	38	22	14	12
Mouth	56	70	71	76	<b>88</b>	64	2	1	20	47	49	68
Guadalupe River												
Upper	6	7	7	7	<b>9</b>	8	5	4	5	7	6	7
Midbasin	11	10	12	14	<b>18</b>	15	5	3	3	5	6	9
San Antonio River												
Upper	5	5	7	7	<b>8</b>	10	11	10	7	7	6	5
Midbasin	21	19	19	18	<b>22</b>	17	13	12	16	18	17	18
Guadalupe + San Antonio Rivers												
Mouth	84	94	82	77	<b>142</b>	117	57	44	69	81	79	82
Nueces River												
Upper	6	5	4	10	<b>16</b>	14	7	5	16	9	4	5
Midbasin	13	16	14	23	<b>50</b>	<b>48</b>	32	23	27	25	17	13
Mouth	10	9	11	11	<b>30</b>	<b>34</b>	13	14	34	25	11	10
Rio Grande												
Upper	3	1	4	8	5	8	<b>13</b>	<b>13</b>	11	11	7	8
Midbasin	106	98	111	107	113	105	<b>157</b>	<b>157</b>	<b>156</b>	132	116	113
Mouth	18	22	16	17	51	49	31	48	<b>70</b>	<b>77</b>	50	18

\*Outlet = Noncoastal outlet from state.

reduce current conditions flows relative to naturalized flows during the late summer, though such differences occur in most basins. Also note that for some locations during some months, return flows from municipalities and reservoir operations and releases result in current-conditions flows being greater than the corresponding naturalized flows.

A better comparison of streamflows between basins is to normalize these flows to account for the differences in watershed area. This parameter is referred to as the “yield” of a particular watershed, and it is estimated by the ratio of the difference in flows between two points on a river or stream to the area of the incremental watershed between the two points. These computed average monthly yields are given in Table 2-3 for major river basins. "Yield" in this context has dimensions of volume of flow per increment of time per area of contributing watershed (acre-foot/square mile/year in Table 2-3), and is exactly the cumulative runoff between the two points on the river or stream. This definition of “yield” should not be confused with the firm water supply produced by a reservoir under drought conditions. As shown by the values presented in Table 2-3, the pattern that emerges is one of increased yield within any one basin as one goes from the upper gage, to the midbasin, and then to the mouth. This intra-basin variation is most pronounced for the large Texas basins that also have strong west to east alignments, such as the Red, Brazos and Colorado basins. The rainfall-runoff pattern manifests itself in an equally pronounced manner when considering differences in yields between basins. The state’s easternmost basins—the Sulphur, Sabine, and Neches—have yields greatly exceeding those found in the western basins—the Nueces and Rio Grande. Also of interest in understanding the state’s hydrology are the differences between the naturalized yields and current-conditions yields for any given location (Table 2-3). As might be anticipated, naturalized yields (with man’s influences removed) typically exceed the current-conditions yields, since the latter reflects the influence of water supply structures and diversions for human use.

## **2.2 Hydrography of Texas Watercourses**

Hydrography refers to the physical variables and processes that govern the movement of water in a watercourse, and includes morphology and bathymetry, water-level variations, internal circulations, sediment scour and deposition, and the transport of water into and out of the watercourse. There are major differences between the hydrography of the stream environment and that of the estuary, which governs the role of streamflow and the habitats created in the watercourse.

### **2.2.1 Streams**

The most obvious physical feature of the stream environment is its longitudinal geometry. Distance along the axis of the stream is measured in many miles, and far exceeds the distance across the stream channel (perhaps tens of feet) and the distance from surface to bottom (perhaps several feet, or even fractions thereof). The term "stream" is used generically: at the small end of the scale are creeks and bayous; at the large end of the scale are rivers. At any point along the stream axis, the flow is the product of velocity averaged over the cross section of the stream times the area of the cross section. Under the influence of gravity, flow is directed from higher elevations to lower elevations, ultimately to the sea. Therefore, apart from rare anomalous conditions, streamflow is always in the same direction along the stream axis, and the terms "upstream" and "downstream" have unambiguous meanings that can be ascertained by consulting either a topographic map or simply a map showing the Gulf.

**TABLE 2-3 WATERSHED YIELDS BASED ON NATURALIZED FLOWS AND WAM CURRENT-CONDITIONS FLOWS**

	<u>Drainage Areas</u>			<u>Annual Watershed Yield</u>					
	Upper	Midbasin	Outlet*	<u>Naturalized Flows</u>			<u>Current-Conditions Flows</u>		
				Upper	Midbasin	Outlet*	Upper	Midbasin	Outlet*
	(Square Miles)			(Acre-Feet/Square Mile/Year)			(Acre-Feet/Square Mile/Year)		
Red River	20,570	39,777	48,030	3	167	557	3	148	546
Sulphur River	505	1,379	3,493	564	698	645	534	664	607
Sabine River	2,258	4,831	9,797	523	574	801	413	541	788
Neches River	1,943	7,569	10,025	440	591	816	418	569	680
Trinity River	6,092	12,864	17,945	244	376	484	157	341	399
Brazos River	14,073	20,870	35,931	47	217	267	32	197	201
Colorado River	13,787	27,622	30,965	29	96	326	11	54	137
Guadalupe River	838	1,519	10,122	151	271	171	142	150	157
San Antonio River	634	2,108	—	165	86	—	133	118	—
Nueces River	5,478	15,461	16,720	23	28	38	37	22	-135
Rio Grande	31,944	123,302	180,918	14	24	21	4	16	-18

\* Outlet denotes either the noncoastal outlet from state or the mouth of the river at the coast.

The next most obvious physical feature is the shape and material of the stream bed and banks. The shape of the stream bed is controlled by erosion of bed materials (or "substrate") and deposition of sediments. A basic distinction is made between fixed bed material, such as exposed rock formations, and moveable bed material, composed of particles of sediment capable of being dislodged and transported by the movement of water. These particles can arise from the material in which the streambed is cut, or can be transported into the stream channel with runoff from the watershed. Most of the channels of most of the streams in the state are composed of moveable bed materials, arising from both transport into the channel and scour of the native material into which the stream channel is incised. The resistance of bed material to erosion, for a given current velocity, is determined by its particle sizes, cohesiveness, and additional competency afforded by aquatic plants.

Bed shape and materials, in addition to being a result of the movement of water, also affect the flow of water by exerting frictional resistance to water movement. Water is forced by gravity to move from higher levels to lower levels, so one of the drivers of streamflow is the slope of the water surface. The level of the water surface is raised by runoff that flows into the stream channel faster than it can move downstream under the influence of gravity. The downstream flow of water is the result of the slope of the water surface working against the friction of the stream bed. The greater the bed material grain size and protuberances (bedforms), the greater the bed friction, and, therefore, the greater the slope of the water surface must be to achieve a given rate of flow. Among other things, this means that at a specific location along the length of a stream, there is a direct relationship between the height of the water surface and the flow in the stream channel, a fact that is exploited in the monitoring of streamflow, since the level of the water surface is far easier to measure than the velocity distribution over the stream cross section.

While the flow across a cross section is almost always directed downstream, the velocity distribution is far more complex, with vortex circulations and sinuous ribbons of higher speed currents separating zones of lower current speed or even stagnation. This complex current structure is often associated with complexities in the stream bed morphology; the two are usually closely related, because the higher-speed currents scour and erode the bed, with the resuspended sediment being transported to lower-speed regions where it is deposited. Not only does the streambed morphology change across a section in the stream channel, it also changes with longitudinal distance down the stream. There are shallow reaches of high sediment deposition, and reaches scoured to greater depths. Important stream channel configurations include bars, riffles, runs, and pools. Bars are accumulations of deposited sediments—usually coarser grained such as sands or gravel—that act as a barrier to flow, forcing the current around the bar. Riffles are shallow reaches over which the water is forced to flow, and usually have cobble and gravel substrates. These substrates are typically clean of fine sediments and aquatic plants because of the locally high current speeds. Riffles are typically sensitive to changes in flow and the associated water depth. Runs are deeper with more moderate current speeds and can have a variety of substrates. Pools are typically deeper, yet with very low current speeds and little surface turbulence. The character of all of these channel configurations changes as flow and hence water level rise and fall.

These variations in stream bed morphology lead to different habitat conditions. The three important determinants of the watercourse for suitability to an organism are exposure to higher-speed currents, depths of water, and nature of the substrate. Many aquatic plants require low (or



zero) current speeds to establish themselves, and those that are rooted require, in addition, fine-grained substrates. Many benthic animals need fine to moderate-sized sediments with some organic matter. Free-swimming organisms may favor greater water depths or higher current speeds, but their young may need access to shallow plant-dominated zones for either food or shelter from predators. As flow rises and falls in a stream environment, the water depths and current speeds vary similarly, so that the habitat characteristics depend fundamentally upon the magnitude of the streamflow.

Flow regimes also facilitate connectivity: the movement and exchange of nutrients; sediments; organic matter; and organisms within the riverine ecosystem, its floodplains, subsurface habitats, and receiving estuaries. Lateral connections between the river and the floodplain are important for maintaining hardwood bottomlands, wetlands, and other diverse riparian systems. Longitudinal connections allow migrating species to fulfill critical life-history events such as successful spawning and recruitment. Vertical connections between the river and its subsurface environment support diverse assemblages of microorganisms and invertebrates and promote productive riverine environments.

Associated with the stream environment are peripheral regions that are regularly inundated when the water levels in the watercourse are elevated. These are "wetlands" and are considered to be particularly important to the ecosystem of the watercourse. Some wetlands may desiccate completely between inundation events, some may retain a shallow cover of water. In Texas, most fall into the former category. Inundation is achieved by runoff events in the stream environment. Texas is estimated to have about 615,000 acres of riverine wetlands.

### **2.2.2 Estuaries**

Those rivers that do not conflow with larger systems or that flow out of the boundaries of the state, eventually empty into the marine environment, either on the coastline of the Gulf of Mexico or into a coastal bay. The sea affects coastal watercourses in a number of ways, whose effects are manifested up a river channel for some distance from its mouth.

Among these marine processes, one of the most important is the more-or-less periodic rise and fall in water level referred to as tides. Tides are dominated by the gravitational effects of the moon, and have characteristic periods tied to the orbit of the moon about the earth. On the Texas coast, the shorter-period tides of 12.4-hour ("semi-diurnal") and 24.8-hour ("diurnal") cycles are much smaller than in other coastal regions of the world. For this reason, the Texas coast is often described as a "microtidal" environment. This relative statement notwithstanding, the typical diurnal tide on the Texas coast has a range of about 3 feet, which is a considerable change in water level over a time period of about a day. There are other longer period components of the tide that are also important on the Texas coast. One of these is a fortnightly variation tied to the elevation of the moon above the horizon. Another is a semi-annual variation (i.e., a complete cycle of high and low water elevation in six months, or two complete cycles in a year), with high water levels in the spring and fall, and low water levels in the winter and summer.

The large surface area of the coastal ocean makes it sensitive to the speed and direction of wind. In addition to generating high surface waves, which mix the water column and erode the land surface in contact with the sea, wind is also capable of moving large volumes of water either into or away from the coastal zone. The resulting variations in water level can completely dominate

the normal tide, and are referred to by mariners as "wind tides," though they are entirely meteorological in origin, not astronomical. On the Texas coast, the high wind speeds and abrupt changes in wind direction that accompany a frontal passage create particularly dramatic water-level variations.

A well-known defining feature of seawater is its high concentration of dissolved salts—about 3.5% by weight—called "salinity." Salinity affects the chemistry of seawater, including the ability of organisms to intake and process that water. Water that lacks appreciable dissolved salts, including rainwater and almost all streamflow derived from runoff, is referred to as "freshwater" to differentiate it from saltwater (and from "brackish" water with intermediate concentrations of salinity). Because dissolved salts increase the density of water, seawater is heavier than freshwater—a fact which influences how the two interact in the coastal environment.

A coastal watercourse in which freshwater and seawater intermix is an estuary. An estuary is a transitional watercourse between the purely terrestrial environment of a freshwater stream and the purely marine environment of the sea, and as a transitional system, it is subject to both terrestrial and marine phenomena. The downstream reach of a river to its mouth, in which occur effects of tides and salinity, is therefore an estuary. A coastal bay into which streams flow and in which seawater intrudes and exchanges is an estuary. As noted in Chapter 1, the main concern of maintenance of environmental flows to the coast is the seven major bays of Texas, shown in Figure 1-2. Into each bay flow several major streams or rivers. The freshwater flow carried into the bay by these streams is referred to as "inflow."

The intermixing of freshwater inflow in an estuary with seawater from the ocean creates a variation in salinity that ranges from seawater values at or near the seaward boundary of the estuary to zero (i.e., freshwater) values upstream in the river channels. This general decline in salinity from ocean to river, or, conversely, the increase in salinity from zero in a river to seawater values near the ocean, is the "estuarine salinity gradient." How quickly salinity changes in space is highly variable over time, and depends upon the level of inflow and the intensity of influx of seawater into the estuary, which is in turn governed by tides, meteorology, wave action, and a few other processes. Seasonal timing of freshwater inflows to bays and estuaries is critically important for providing proper conditions for reproduction and growth. In particular, seasonal high-flow events must be of sufficient volume and duration to affect salinity along estuarine gradients.

Most aquatic organisms, especially animals, have physiologies specifically tuned to either the freshwater or the saltwater environment, and cannot survive in water of radically different salinity. Such organisms, i.e. almost all freshwater and marine species, are poorly equipped for the estuarine environment. A minority, however, can tolerate a wide range of salinities, and these are the predominant organisms in the estuary. Even these, however, may function better in certain ranges of salinity between fresh and seawater values than over the full range of salinities that occur in an estuary. Where the salinity gradient occurs in an estuary, and how quickly it changes with distance, can be important habitat determinants for these species. An additional factor that is important in the salinity of the Texas bays is the net loss of water from the surface of the water due to the excess of evaporation over precipitation. (Salts in solution do not participate in the evaporation, but are left behind in the water column, thus increasing the salinity of the water.) In the more arid conditions of the South Texas coast, the evaporative loss becomes

substantial, and the salinities in these bays are often "hypersaline" (i.e., exceeding the salinity of seawater).

The Texas bays are a specific type of estuary, known as "lagoonal," and one of their important features is their near isolation from the sea by barrier islands. Exchange between the bay and the sea is confined to relatively narrow passes or "inlets" through the barrier island system. Much of the energy of the semidiurnal and diurnal tides is lost as the tide propagates through these inlets, making these components of tide variation inside the bays even smaller than on the open coast. In contrast, the longer period tides (the fortnightly and semi-annual) propagate into the bays with little loss of energy, and represent major factors in the exchange of water between the bay and the sea. Meteorological water-level variations are as important within the bays as on the open coastal waters, and frontal passages can create substantial differences between the water level inside the bay and that of the Gulf Coast, which entail high currents and intense exchange through the inlets. As will be seen, these passes are important to organisms in the estuaries because the majority of these organisms migrate between the estuary and the sea at different stages of their life cycle.

The physiography of the Texas bays has been modified by the human presence for millennia—from the extensive shell middens of prehistoric natives to the petrochemical complexes of the Twentieth Century. Much of the shoreline, both within the bays and on the Gulf shorefront, has been modified by bulkheads, seawalls, and revetment, all to facilitate human development as close as possible to the water. Subsurface fluid withdrawal (both water and petroleum) have caused subsidence and the associated increased water depths in several of the bays. The bays are crisscrossed with dredged channels to permit navigation through these generally shallow systems. Most of the channels are typically 12–15 feet deep for tows and boat traffic. These include service channels to petroleum wells, barge channels to minor port facilities, and the Gulf Intracoastal Waterway, which runs from Sabine Pass to Port Isabel.

A few of the channels connect the bays to the sea for access of seagoing vessels to the major ports of Texas. These channels are typically greater than 40 feet in depth to accommodate the deep drafts of freighters and tankers. These channels pass through the major inlets to the bays, and protection of the channels from siltation and the channel traffic from adverse currents has necessitated construction of jetties on either side of the inlet, extending as much as several miles into the Gulf of Mexico. These jetties intercept the normal long shore transport of sand on the coast and substantially modify the bathymetry of the inlet, even outside of the dredged areas. Two navigation channels on the Texas coast—Mansfield and Matagorda Entrance—have been dredged through the barrier island, creating new inlets. In the case of the latter, this has stimulated the shoaling and closure of the natural inlet to Matagorda Bay.

In the periphery of the Texas bays are wetlands, inundated by water-level excursions. In the bay and estuary, these water-level excursions can be caused by tides, wind responses, flood events, or a combination of the three. The peripheral wetlands in the Texas bays are shallows, usually vegetated, whose inundation may occur occasionally or frequently. Those wetlands in the depositional lobes of deltas are occasionally inundated by freshwater floods entering the bay from the river, as well as by tides and meteorologically driven rises in the waters of the bay. Vegetated wetlands adjacent to the bay but remote from the mouths of rivers (and their deltas) are mainly inundated by the water levels of the bay. A special case of this is the tidal flats of the Texas south bays, covered by a blue-green alga that is dormant until wetted by infrequent high

tides or seasonal water-level rises. Estuarine wetlands are estimated to total some 570,000 acres in Texas (Moulton et al. 1997).

The WAM simulations afford an ability to quantify the cumulative effects on inflows into the principal bays. In Table 2-4 are tabulated the monthly median inflows for "naturalized" conditions and "current conditions" (refer to Section 2.1.3 for the definition of these WAM-related conditions). Also included in the table are the monthly median inflows, as simulated with the WAM for conditions with full utilization of all water rights in each basin at their authorized levels of appropriation (i.e., diversions and reservoir storage, referred to as "Full Approp.>"). These are the inflows to the bays if all water rights were fully utilized all at the same time, year after year, which is likely an extreme scenario.

With regard to the current-conditions inflows, it is apparent that the reduction in inflow from the naturalized-conditions case indicated by these results ranges from substantial (for Matagorda Bay) to minor (for Corpus Christi Bay). The inflows corresponding to the full water rights utilization case indicate significantly greater reductions from the naturalized inflows because of the higher consumption of streamflows by upstream users. Reductions greater than 50% are typical for all of the bays, except for the Copano/Aransas system. Also, it is significant to note that the relative or percentage reductions in inflow from naturalized conditions to both the current-conditions and the full-appropriation conditions typically vary seasonally. For example, in Sabine Lake, April inflows for the current-conditions case are indicated to have decreased less than 10% from the naturalized conditions, while August inflows have decreased about 50%.

It should be noted that, in general, only the indicated riverine inflows are considered in the results presented in Table 2-4; inflows from other smaller tributaries and peripheral drainage from the coastal regions are not included. Since these additional inflows reflect little human development compared to the principal rivers, it is likely that the comparisons in Table 2-4 overestimate somewhat the impact of the developed water-use conditions. It should also be noted that these five-to-six decade simulations with the WAM assume that all of the specified water-use conditions are in effect throughout the entire simulation period, whereas the development represented by full appropriation has not yet occurred, and has not been manifest over the period of simulation. Therefore, Table 2-4 is not so much a measure of the impact of human activities as it is the potential for such impact.

Surface water in Texas is owned by the state and held in trust for the citizens of the state [Texas Water Code §11.0235(a)]. Texas, like most western states, has adopted the prior appropriation doctrine as the basis of allocating state water resources. The state, through the TCEQ, authorizes and administers water rights to use state water [Texas Water Code §5.013(a)(1)]. Each water right has an assigned priority date. The priority date determines the water user's priority to use water, with the earliest priority date having the senior right. Thus, among appropriators, the principle of "first in time, first in right" applies [Texas Water Code §11.027]. If during times of shortage, the quantity of water in a stream is insufficient to meet all of the demands for water, those water rights with earlier priority dates (senior appropriators) will be entitled to obtain their allotted water first; those who appropriated water later (junior appropriators) may receive only some, or none, of the water to which they have permitted rights.

**TABLE 2-4 MEDIAN MONTHLY NATURALIZED, CURRENT-CONDITIONS, AND FULL-APPROPRIATION INFLOWS TO MAJOR TEXAS BAYS**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(1,000s of Acre-Feet)												
<b>Sabine Lake (Neches + Sabine Rivers)</b>												
Naturalized	1,352	1,646	1,700	1,314	1,312	728	335	163	164	189	348	950
Current Cond.	1,314	1,592	1,641	1,220	1,213	564	173	75	79	103	309	896
Full Approp.	606	876	950	578	661	180	31	19	19	19	69	327
<b>Galveston Bay (Trinity + San Jacinto Rivers)</b>												
Naturalized	512	720	603	645	1,035	583	237	98	149	186	304	538
Current Cond.	462	627	512	460	910	457	153	78	121	151	286	470
Full Approp.	197	293	317	262	534	226	31	23	32	28	56	126
<b>Matagorda Bay (Colorado + Lavaca/Navidad Rivers)</b>												
Naturalized	152	165	140	230	449	283	144	103	191	162	127	140
Current Cond.	87	96	86	110	162	121	18	20	63	68	60	84
Full Approp.	71	73	47	46	84	38	14	5	20	32	41	57
<b>San Antonio Bay (Guadalupe + San Antonio Rivers)</b>												
Naturalized	93	104	96	95	163	145	83	67	88	97	89	89
Current Cond.	84	94	82	77	142	117	57	44	69	81	79	82
Full Approp.	65	71	60	53	121	91	34	27	51	62	65	64
<b>Copano/Aransas Bays (Mission + Aransas Rivers)</b>												
Naturalized	2	3	3	2	5	5	2	1	4	4	3	2
Current Cond.	2	3	3	2	5	5	2	1	4	4	4	2
Full Approp.	2	3	3	2	5	5	2	1	4	4	3	2
<b>Corpus Christi/Nueces Bays (Nueces River + Oso Creek)</b>												
Naturalized	7	7	7	10	43	45	17	16	39	26	9	5
Current Cond.	10	9	11	11	30	35	14	14	38	26	11	10
Full Approp.	1	1	1	2	8	10	2	5	12	9	1	2

### 3. SURFACE WATER REGULATION IN TEXAS

#### 3.1 Water Rights System

One exception to the “first in time, first in right” principle relates to water rights granted on the mainstem of the Rio Grande below Amistad Reservoir. In the Lower Rio Grande Valley court's adjudication of rights on the Rio Grande below Falcon Reservoir, priority was assigned based upon the classification of use, rather than the date of the filing, claim, or application. The decision was *The State of Texas v. Hidalgo County Water Control & Improvement District No. 18*, 443 S.W.2d 728 (Tex. Civ. App. - Corpus Christi, 1969). *writ ref'd n.r.e.* This adjudication was done, in part, to address rights granted under Spanish and Mexican law and to provide a system that would attempt to assure adequate water supplies for domestic and municipal water users during times of shortage. Under the court's ruling, rights for domestic, municipal, and industrial uses have a higher priority and may be curtailed during times of low flows only after the supplies for irrigation, mining, and other uses have been fully diminished. Through the Middle Rio Grande adjudication process, this class-based priority system also was later adopted for water rights on the Rio Grande between Falcon Dam and Amistad Dam.

Another exception exists under the "futile call" doctrine. This principle of western water law provides that if the water reaching a senior appropriator's place of diversion is insufficient for beneficial use—even if all upstream junior appropriators were not diverting water—the TCEQ may allow the upstream junior appropriators to use the water.

Certain types of surface water uses are allowed that fall outside the prior appropriation system. These include common law riparian rights, as well as various exempt uses that are set forth by statute, such as impoundments for domestic and livestock purposes and wildlife management (discussed below). While most agree that common law riparian rights have a superior right to permitted uses, the relative priority of the various statutory exemptions is subject to considerable debate among water law practitioners across the state.

#### 3.2 Water Rights Permitting

Anyone who wants to use surface water in Texas must first get a water right from the TCEQ, unless the water is used under a claim of common law riparian rights or for the “exempt uses” listed in the Texas Water Code. Lands granted out of public ownership by the Republic or State of Texas between January 20, 1840 and July 1, 1895 may still carry with them a common law riparian right to use water for domestic and livestock purposes. In addition, the Texas Legislature has created several exempt uses that are allowed without the need to obtain a water rights permit from TCEQ. Exempt uses are:

*Domestic and livestock use.* This refers to water impounded on a person's own property for purposes of watering range livestock, to meet household needs, or to irrigate a yard or home garden. The average allowable volume of water that can be stored in any 12 consecutive months is 200 acre-feet or less [Texas Water Code §11.142(a)].

*Wildlife management.* This refers to the impoundment of up to 200 acre-feet of water on one's own property for noncommercial fish and wildlife management purposes. This reservoir must also be on qualified open-space land, as defined by §23.51 of the Texas Tax Code [Texas Water Code §11.142(b)].

*Emergency use.* County fire departments, rural fire departments, and other similar public services may draw water from local reservoirs, when needed, to deal with an emergency [30 Texas Administrative Code §297.26].

*Other specified uses.* The Water Code's less-common exempt uses may include the use of water in fish or shrimp farming in brackish or marine water, in drilling for and extracting oil, or for sediment control in surface coal mines. Retaining water with spreader dams or terraced contours is also considered an exempt use [Texas Water Code §§11.142(c) & (d), §11.1421].

The types of water rights for which permits are issued are: (1) perpetual rights, including certificates of adjudication and permits, and (2) limited-term rights, including term permits and temporary permits.

The purposes for which surface water may be appropriated include the following [Texas Water Code §11.023]:

1. domestic and municipal uses, including water for sustaining human life and the life of domestic animals;
2. agricultural uses and industrial uses, meaning processes designed to convert materials of a lower order of value into forms having greater usability and commercial value, including the development of power by means other than hydroelectric;
3. mining and recovery of minerals;
4. hydroelectric power;
5. navigation;
6. recreation and pleasure;
7. public parks;
8. game preserves; and
9. any other beneficial use.

The Texas Water Code does not expressly authorize the TCEQ to grant water rights exclusively for: (1) instream flows dedicated to environmental needs or inflows to the state's bay and estuary systems, or (2) other similar beneficial uses [Texas Water Code §11.0235(d)]. However, this does not prohibit the TCEQ from issuing an amendment to an existing permit or certificate of adjudication to change the use to or add a use for instream flows dedicated to environmental needs or bay and estuary inflows [Texas Water Code §11.0237(a)].

A right to use state water under a permit or a certified filing is limited not only to the amount specifically appropriated (permitted) but also to the amount which is being or can be beneficially used for the purposes specified in the appropriation; all water that is not beneficially used is considered to not be appropriated [Texas Water Code §11.025]. Hence, to appropriate state water means to divert, store, or use or intend to divert, store, or use a specific amount of water

beneficially for one or more of the purposes stated above. No right to appropriate water is perfected unless the water has been beneficially used for a purpose stated in the original declaration of intention to appropriate water or stated in a permit issued by the TCEQ or one of its predecessors [Texas Water Code §11.026]. The Water Code provides that the remedy for non-use is cancellation of the water right. If a water right has not been used for 10 or more years, and one of the exceptions in Texas Water Code §11.173 or §11.177 does not apply, the water right can be cancelled after an evidentiary hearing with appropriate findings.

The Texas Water Code provides that the TCEQ may grant an application for a new or additional appropriation of water only under the following conditions [See Texas Water Code §11.134]:

1. the application meets all necessary requirements;
2. unappropriated water is available in the source of supply;
3. the water will be beneficially used;
4. the use will not impair existing water rights or vested riparian rights (this is commonly referred to as the "no injury" rule);
5. the use will not be detrimental to the public welfare;
6. the application considers the effects on groundwater and groundwater recharge;
7. the application addresses a water supply need in a manner that is consistent with the State Water Plan and an approved regional water plan, unless the Commission determines that conditions warrant waiver of this requirement; and
8. the applicant has provided evidence that reasonable diligence will be used to avoid waste and achieve water conservation.

### **3.3 Water Availability**

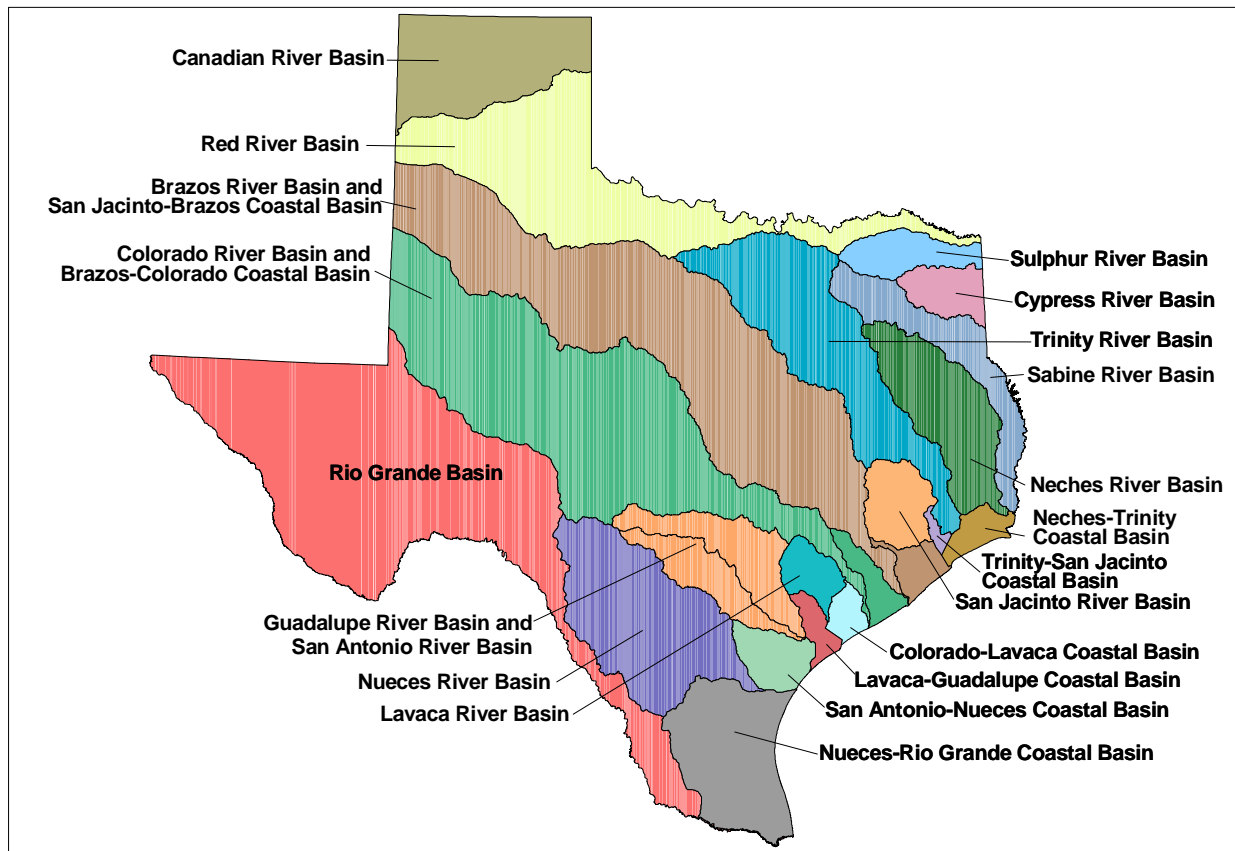
The TCEQ may grant an application for a new or increased appropriation of water if there is sufficient "unappropriated water" available in the source of supply [Texas Water Code §11.134(b)(2)]. Unappropriated water is defined in 30 Texas Administrative Code §297.1(54) of the TCEQ rules as the amount of state water remaining in a watercourse after taking into account all existing water rights valued at their full authorized amounts and conditions.

TCEQ staff prepare water availability analyses for water right permit applications to determine whether water is available for appropriation as requested by the applicant. A water availability analysis applies to an application for the following [Texas Water Code §11.122(b); 30 Texas Administrative Code §295.158(b)–(c)]:

- 1) a new appropriation;
- 2) an increase in appropriation;
- 3) a change (increase) in diversion rate; or
- 4) a change in diversion point.

To estimate the amount of unappropriated water available, staff use hydrologic computer models and gaged streamflow data adjusted to the applicant's location. These models are referred to as Water Availability Models, or WAMs. In response to the requirements of Senate Bill 1 of the 75<sup>th</sup> Legislature (1975) and House Bill 76 of the 76<sup>th</sup> Legislature (1977), the TCEQ now has developed 20 such models covering all river and coastal basins in Texas. The map of Texas in Figure 3-1 shows the different WAMs for all of the basins.





**FIGURE 3-1 WATER AVAILABILITY MODELS FOR TEXAS BASINS**

All of the current WAMs utilize the Texas A&M “WRAP” computer program (Wurbs 2003) as the basic simulation tool for performing the required water availability analyses. The WRAP computer program, or model, simulates the management and use of the water resources of a river basin, or multiple-basin region, under a priority-based water allocation system for a specified set of hydrologic conditions. The program was developed specifically for water rights in Texas subject to the prior appropriation doctrine; however, it has been extended to also represent the class-based water rights priority system (type of use) for the Rio Grande water rights downstream of Amistad Reservoir.

The WRAP model performs sequential monthly water volume accounting computations for an entire river basin or system of river basins. Specified constant annual water use requirements, which vary over the 12 months of the year, are combined with sequences of “naturalized” streamflows and reservoir evaporation rates reflecting historical hydrologic and climatic conditions. For each month of the simulation period, which typically may extend over 50 or so years, water rights requirements are met in priority order. Water rights may include diversions, reservoir storage, instream flows, return flows, and hydroelectric power generation. Multiple-reservoir system operations are based on balancing the percentage full of specified zones in the reservoirs included in the system for particular water rights.

Naturalized flows are the flows which would be in the streams if the effects of the most significant of "man's activities" were removed (i.e., dams, diversions, etc.). The naturalized streamflow database for all of the current WAMs extend from 1940 through either 1996, 1998, or 2000, depending on the basin. These periods of record include severe drought conditions; hence the critical drought of record for each basin is included in the water availability analysis. In deriving naturalized flows for a particular streamflow gage location, first, the amount of water historically diverted plus changes in reservoir storage and evaporative losses upstream of the gage are added to the historical flows. The data used are mainly from gage and reservoir records and water use reported to the TCEQ by water right holders. Second, the historical effluent discharges and estimated return flows upstream of the gage are subtracted to determine the naturalized flows at the gage. All of these calculations are performed on a monthly basis using the following equation:

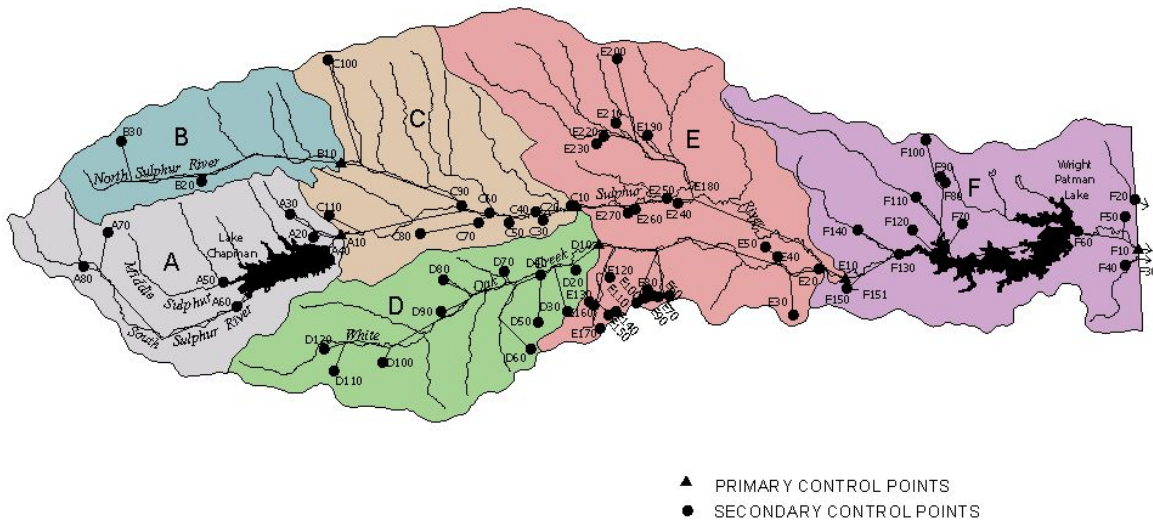
$$\text{Naturalized Flow} = \text{Gaged Flow} + \text{Diversions} + \text{Reservoir Storage Change} - \text{Return Flows}$$

The generalized WRAP computer model has the capability to simulate a stream/reservoir/use system involving essentially any stream tributary configuration. Interbasin transfers of water can be included in the simulation. Closed loops, such as conveying water by pipeline from a downstream location to an upstream location on the same stream or from one tributary to another tributary, can be modeled. The system configuration is represented in the model by a set of control points.

Input data for the WAMs include: naturalized monthly streamflows at each control point covering the simulation period; relative control point locations; watershed parameters describing drainage area size, runoff characteristics, and average annual rainfall amounts for each control point; diversion amounts, reservoir storage capacities, priority dates, type of use, and return flow specifications for each water right; storage-versus-area relationships for all reservoirs simulated; monthly reservoir net evaporation rates for the simulation period; and monthly water use distribution factors for each type of water use.

Simulated results from the WAMs include monthly diversions and reservoir storage for individual water rights, monthly regulated streamflows and the monthly amounts of remaining unappropriated water at selected points within a basin(s); these results can be summarized by a variety of user-specified tables and reliability indices. In essence, the WRAP program performs the necessary computations required to fully support the water availability analysis process for evaluating applications for new appropriations or amendments.

A typical application of the WRAP model is illustrated by the water rights network shown in Figure 3-2. This example is for the Sulphur River basin in northeast Texas. The control points identified on the map of the basin represent locations in the WRAP model where water availability computations are performed, and they include the actual locations of all existing water rights. The Primary Control Points reflect locations where monthly naturalized streamflows have been developed and specified as inputs to the model. The Secondary Control Points represent diversions and storage nodes for individual water rights and other points of interest where the water availability outputs from the model are simulated. During the simulation process, naturalized streamflows at the Secondary Control Points are derived from those specified at the Primary Control Points, taking into consideration drainage area size, variations in runoff characteristics, and general rainfall patterns.



**FIGURE 3-2 CONTROL POINTS IN SULPHUR BASIN WAM**

In performing water availability analyses using the WAMs, diversions and reservoir storage for each active water right are simulated in priority order, assuming every right exercises its full authorized amount. Reservoir storage, evaporative losses, spills, and priority releases are also determined in the simulation process, and unappropriated water is estimated. The unappropriated water is the quantity of naturalized flow left at any point within the stream system of a basin after simulating all existing water rights, assuming all rights use their full appropriation and all reservoirs are filled to capacity, taking into account evaporative losses.

After estimating the amount of water available for appropriation on a monthly basis at an applicant's location, TCEQ staff determine how and when the water may be diverted without affecting existing water rights. Streamflow restrictions and other conditions may be necessary to protect senior water rights, environmental water needs, and/or groundwater supplies. These special conditions typically provide that no appropriation (either diversion from a stream or additional storage in an on-channel reservoir) may occur when the streamflow passing just downstream of the diversion point or just below the impoundment is less than a certain flow rate in cubic-feet-per-second (cfs).

For each application, the water availability analysis includes simulations of how often the requested amount (distributed to monthly demands) can be met from estimates of streamflow available in the source of supply and estimates of unappropriated water. If a restriction (special condition) has been recommended for the protection of senior water rights and/or environmental water needs, this restriction is used (deducted from available streamflow) in the simulation. The results of the simulation are used to determine if water is available for appropriation at the applicant's location in sufficient quantities and times to justify the granting of the permit.

Although the Water Code provides that an application may be granted, in whole or in part, only if there is unappropriated water available in the source of supply, it does not specifically provide that the full requested amount of unappropriated water must be available 100% of the time for the application to be granted. Accordingly, the TCEQ has adopted rules for determining whether there is sufficient unappropriated water available to grant an application.

The TCEQ rules provide that in the case of a proposed direct diversion from a stream for irrigation use, approximately 75% of the water requested when distributed on a monthly basis must be available at least 75% of the time [30 Texas Administrative Code §297.42 (c)]. The statistics pertaining to "percent of the time" generally refer to how many years the entire demand is met when the demand is distributed on a monthly basis. When at least 75% of the applicant's requested demand when distributed monthly cannot be met in at least 75% of the years, then an analysis of the specific monthly demands is made. In this consideration, the statistic is based on the number of months when water is requested by the applicant. If the applicant's monthly demands can be met in at least 75% of the months with a non-zero distributed demand, the application may be granted.

If there is insufficient unappropriated water available to grant a perpetual water right, the TCEQ may grant the water right for a term of years if the existing affected downstream water rights are not fully developed and the term permit would not adversely affect the perfection of those rights [Texas Water Code §11.1381]. The rules also provide that lower availability percentages may be acceptable if the applicant can demonstrate that a long term, reliable, alternative source (or sources) of water of sufficient quantity and quality are economically available to the applicant to make the proposed project viable and ensure the beneficial use of state water without waste. Projects that are not required to be based on the continuous availability of water are evaluated on a case-by-case basis based on whether the project can be viable for the intended purposes [30 Texas Administrative Code §297.42(d)].

Finally, it should be noted that the water availability analysis does not expressly account for unrecorded vested riparian water rights or statutorily exempt uses (primarily domestic and livestock uses). The only caveat to this is that those riparian or exempt uses that have been in existence for some time are indirectly accounted for in the gage records for the basin from which the naturalized flows were derived for the WAMs. New or expanded riparian or exempt uses, however, are not accounted for.

### **3.4 Unappropriated Water**

As noted above, before a new water right may be granted in Texas, the TCEQ must find that sufficient "unappropriated water" is available in the source of supply. To determine unappropriated water, the TCEQ staff uses the WAMs, assuming no return flows are discharged back into the stream system (WAM Run 3). Since the naturalized flows within a basin vary by location and time (see Chapter 2, Tables 2-1 through 2-3), the amount of water remaining after deducting for all authorized or permitted uses of water—the difference being referred to as unappropriated water—will also vary.

Table 3-1 tabulates monthly quantities of unappropriated water on principal rivers in Texas based on the WAM Run 3 results (full utilization of all existing water rights). The same mainstem points on each river as were used in Chapter 2 are included in the table for display: the USGS gage location farthest inland on the river (Upper), a gage location approximately midway down the river (Midbasin), and the outlet of the river from the state (Outlet or Mouth), which for most rivers is the mouth at the coast. The displayed monthly quantities of unappropriated water represent median values for the historical period of record as produced by the WAMs for each of the basins. Hence, more than the unappropriated water for each month in the table is available for

half of the time, and conversely, less than the indicated values is available the other half of the time. Readily apparent is the absence of unappropriated water in much of the western two-thirds of the state, beginning with the Brazos basin and heading westward. Even in the eastern third of the state, the upper portions of most basins indicate little unappropriated water available. Another pattern that emerges is that when there is unappropriated water available, the amount is typically much less during the summer and early fall months when naturalized flows typically are less and municipal and agricultural demands are highest.

### **3.5 Firm Yield Operations**

Historically, a constraint on the granting of municipal rights has been the limitation that diversion amounts be limited to the “firm yield” when a reservoir is used as the sole source of water [30 Texas Administrative Code §297.42(e)]. The reason for this was the necessity to have a secure and dependable water supply for uses necessary to protect the public health, safety, and welfare. “Firm yield” is that amount of water, based upon a simulation utilizing available streamflows, that could be withdrawn annually from a reservoir if it had been in place during the worst drought of record [30 Texas Administrative Code §297.1(20)]. When performing this simulation, the full exercise of upstream senior water rights is assumed, as well as the passage of sufficient water to satisfy all downstream senior water rights and flows necessary for environmental needs.

A storage reservoir for municipal water use may be authorized with a permitted annual diversion in excess of its “firm yield” when alternative sources of water supply, such as groundwater, other reservoir systems, or other means are available to satisfy needs during drought periods when the reservoir's supply capabilities would be exceeded. When an annual diversion in excess of the firm yield is authorized, additional special conditions for the protection of environmental needs and existing water rights may be necessary. In addition, the applicant will need to demonstrate the reliability of the alternative sources of supply. Generally, only municipal uses are limited to firm yield authorization [30 Texas Administrative Code §297.42(e)].

### **3.6 Permitting Considerations for Environmental Flows**

In reviewing an application for a permit to store, take, or divert water, the TCEQ assesses the impacts the issuance of the permit may have on existing instream uses, fish and wildlife habitat, water quality, and bays and estuaries [Texas Water Code §§11.147–11.152] and generally must “include in the permit, to the extent practicable when considering all public interests, those conditions considered by the Commission necessary to maintain existing instream uses and water quality of the stream or river to which the application applies.” [Texas Water Code §11.147(d)] Applications that may present a potential adverse impact to the environment include any new appropriation and/or amendment relating to the following aspects of water rights [Texas Water Code §§11.122(b) and 11.085(k)2(F); 30 Texas Administrative Code §295.158(b)-(c)]:

1. new appropriation, or an increase in the total appropriative amount;
2. significant change in point of diversion;
3. change in rate of diversion; or
4. interbasin transfer.

**TABLE 3-1 MEDIAN MONTHLY VALUES OF UNAPPROPRIATED WATER  
BASED ON WAM RUN 3 RESULTS**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(1,000s of Acre-Feet)												
Red River												
Upper	1	1	1	1	8	10	1	0	1	1	1	1
Midbasin	28	42	91	80	207	181	20	0	30	30	23	30
Outlet	197	294	335	409	681	351	112	33	72	171	139	146
Sulphur River												
Upper	0	0	0	0	0	0	0	0	0	0	0	0
Midbasin	14	37	50	38	67	15	0	0	0	0	9	29
Outlet	132	169	194	129	169	43	0	0	15	17	80	95
Sabine River												
Upper	0	0	36	30	13	0	0	0	0	0	0	0
Midbasin	0	0	141	89	68	0	0	0	0	0	0	0
Mouth	160	250	358	192	164	70	25	16	15	13	30	180
Neches River												
Upper	44	57	64	62	66	24	0	0	0	0	0	27
Midbasin	248	422	416	317	457	101	0	0	0	0	119	137
Mouth	445	625	592	386	496	110	6	3	3	6	39	219
Trinity River												
Upper	57	57	73	110	187	117	22	13	24	24	26	32
Midbasin	195	266	330	299	542	279	84	32	46	96	100	167
Mouth	366	543	476	561	849	498	192	59	101	144	224	385
Brazos River												
Upper	0	0	0	0	0	0	0	0	0	0	0	0
Midbasin	2	12	6	5	64	0	0	0	0	0	0	11
Mouth	137	192	134	182	579	212	23	0	21	29	72	116
Colorado River												
Upper	0	0	0	0	0	0	0	0	0	0	0	0
Midbasin	0	0	0	0	0	0	0	0	0	0	0	0
Mouth	21	30	18	11	14	2	0	0	1	6	29	19
Guadalupe River												
Upper	0	0	0	0	0	0	0	0	0	0	0	0
Midbasin	0	0	0	0	0	0	0	0	0	0	0	0
San Antonio River												
Upper	0	0	0	0	0	0	0	0	0	0	0	0
Midbasin	0	0	0	0	0	0	0	0	0	0	0	0
Guadalupe + San Antonio Rivers												
Mouth	65	71	60	53	121	91	34	27	51	62	65	64
Nueces River												
Upper	0	0	0	0	0	0	0	0	0	0	0	0
Midbasin	0	0	0	0	0	0	0	0	0	0	0	0
Mouth	0	0	0	0	0	0	0	0	0	0	0	0
Rio Grande												
Upper	0	0	0	0	0	0	0	0	0	0	0	0
Midbasin	0	0	0	0	0	0	0	0	0	0	0	0
Mouth	0	0	0	0	0	0	0	0	0	0	0	0

For an amendment to a water right, the assessment of potential adverse effects and corresponding permit limitations apply only to the scope of the proposed change. Applications are evaluated on a case-by-case basis to determine if environmental protection is required.

### **3.6.1 Rivers and Streams**

For instream uses and fish and wildlife habitat in rivers and streams, several assessment techniques may be used by the TCEQ to evaluate potential effects of actions associated with water right applications. They range from descriptive statistical summaries of hydrologic data to intensive field studies. For example, average annual or median monthly streamflow data based upon gage records may be used to develop permit conditions to protect aquatic habitat, or a comprehensive field study may be performed to develop site-specific information relating streamflow magnitudes to habitat type and coverage.

Information provided by the TPWD and USFWS concerning the ecological characteristics of the area and the occurrence of species—including threatened and endangered species and species of special concern—is considered and examined, as well as scientific literature that may be available for the area in question. In addition, the Ecologically Unique River and Stream Segments information compiled by TPWD is considered. TCEQ staff also use the *State of Texas Water Quality Inventory*, *Clean Water Act Section 303(d) List* and the *Schedule for Development of Total Maximum Daily Loads* (as periodically updated), the *Texas Surface Water Quality Standards* [30 Texas Administrative Code Chapter 307], and the TPWD report, *An Analysis of Texas Waterways* (1979), as well as any other available documents or publications that may contain relevant information. On a case-by-case basis, the Resource Protection Team may collect site-specific information on water quality, stream habitat, or biological characteristics of the area. Information is also obtained regarding water quality, previous biological assessments, and permitted discharges [30 Texas Administrative Code §297.56(a)].

The characteristic hydrology of the area is reviewed using historical flows from gage records and 1:24,000-scale U. S. Geological Survey topographic maps. For perennial streams, reviewers work with staff hydrologists to calculate the monthly median flows based upon daily flows and water availability. Monthly median streamflows often are used to calculate appropriate streamflow restrictions that will protect the hydrology of the stream and the flow-dependent instream habitat. This is accomplished by using the results of detailed studies of the stream in question, or by applying default assumptions for Texas streams when no detailed study has been performed. In addition, the seven-day, two-year low flow (7Q2) value is calculated from gage records or obtained from the State of Texas Water Quality Standards. The 7Q2 is defined as the lowest average flow for seven consecutive days that is expected to recur every two years, as statistically derived from historical daily flow data. In most instances, minimum flows will not be allowed to fall below the 7Q2 value, since this flow statistic is used as the critical condition for the application of water quality standards and water quality permitting. This estimate of critical conditions is utilized in the environmental assessment to ensure the protection of significant aquatic uses dependent upon the maintenance of water quality.

TCEQ staff often recommends that applicants conduct on-site investigations for areas with unique habitats, threatened or endangered species, and where habitat mitigation plans are required. At a minimum, these assessments include a visual inspection of the affected terrestrial and aquatic habitat, and limited hydrologic, water quality, and biological sampling. In addition,

technical reviewers may require groundwater quality analyses if an applicant proposes to utilize groundwater as part of the project.

In 2001, Senate Bill 2, in part, amended §16.059 of the Texas Water Code to include the collection of instream flow data and the conduct of studies to establish appropriate environmental flows for protecting instream uses. The legislation directed the TPWD, TCEQ, and TWDB, in cooperation with other appropriate governmental agencies, to determine appropriate methodologies for determining flow conditions in the state's rivers and streams necessary to support a sound ecological environment. A programmatic workplan was developed in 2002 that presented an overview of the proposed instream flow program and prioritized several stream segments for field studies. The state has requested that the National Academy of Sciences review the proposed methodology and provide recommendations.

Once the information is gathered and assimilated, a recommendation is made on the type of restriction or condition which might be required to satisfy environmental concerns. Factors which contribute to the inclusion of a streamflow restriction include: (1) the perennial nature of the stream; (2) aquatic life uses and biological integrity of the stream; (3) water quality; (4) presence of federally listed threatened and endangered species; and (5) established recreational uses. In addition to streamflow restrictions, mitigation or other conditions may be recommended for altered, inundated, or destroyed terrestrial or riparian habitats, as well as possible adverse water quality impacts.

The streamflow restrictions included in water rights by the TCEQ represent minimum flows that must be passed downstream before any streamflow can be diverted or stored or used for the authorized purpose stipulated in a water right. Examples of such streamflow restrictions are described below for specific water rights. A summary of the number of such permits or permit amendments that have been issued by the TCEQ in the different basins in the state along with the associated total authorized diversion amount is presented in Table 3-2.

*Paul Weinman* – A permit was issued by the TCEQ authorizing a diversion not to exceed 2,448 acre-feet per annum from the Brazos River into an off-channel reservoir. A condition was placed in this permit that provides maintenance flows for "...existing instream uses and senior and superior downstream water rights..." which allows diversions of water from the river only when the streamflows are equal to or greater than prescribed monthly values.

*Canyon Lake Amendment* – The TCEQ issued an amendment to the Guadalupe-Blanco River Authority's existing Canyon Lake water right that authorized the diversion and use of an additional amount of water (not to exceed 57,100 acre-feet/year) on a non-firm basis. The TCEQ staff recommended that streamflows be maintained in the Guadalupe River below Canyon Dam to satisfy certain hydroelectric water rights and to augment streamflows to protect and support the fishery below the dam. The required minimum flows (which vary by month) are conditioned on inflows to the reservoir (flow pass-throughs). Also, at least a portion of the water passed through the reservoir under this condition is to remain in the river until it reaches the salt water barrier near the mouth of the river.



**TABLE 3-2 SUMMARY OF WATER RIGHTS BY BASIN  
WITH ENVIRONMENTAL INSTREAM FLOW RESTRICTIONS**

Basin	Number of Water Rights With Instream Flow Restrictions	Total Authorized Diversion Amount (acre-feet/year)
Canadian	0	0
Red	16	19,221
Sulphur	4	78,540
Cypress	1	0
Sabine	5	228,244
Neches	16	13,754
Trinity	22	53,771
San Jacinto	13	6,945
Brazos	59	178,303
Colorado	25	191,798
Lavaca	27	16,300
Guadalupe-San Antonio	170	307,634
Nueces	28	1,381
Rio Grande	1	40,000
Total	386	1,235,891

*Lakeside Club Diversion* – The Lakeside Club was granted a permit by the TCEQ, authorizing the maintenance of an off-channel reservoir and a diversion from White Oak Bayou in the Trinity Basin not to exceed 75 acre-feet per annum. The permittee is allowed to divert only when the flow in the bayou equals or exceeds 6.0 cfs.

*Lakes Buchanan and Travis* – In 1934, the Texas Legislature created the Lower Colorado River Authority (LCRA) as a conservation and reclamation district. The LCRA was charged with managing the lower Colorado River and its tributaries for multiple beneficial purposes.

In 1988, after a long series of negotiations among the LCRA, the City of Austin, and the Texas Water Commission, Judge J.F. Clawson of the 264<sup>th</sup> Judicial District of Bell County, Texas signed a Final Judgment and Decree relating to LCRA’s and the City of Austin’s respective water rights. Under the Judge’s final decree, LCRA was required to prepare and implement, subject to approval by the Texas Water Commission, a reservoir operation plan for lakes Buchanan and Travis (the main waters supply reservoirs in LCRA’s Highland Lakes reservoir system). This document has come to be known as the LCRA Water Management Plan (WMP). In addition to determining the firm yield of the

system and addressing drought management, the WMP addresses two notable concerns: (1) instream flows for the lower Colorado River; and (2) freshwater inflows for Lavaca-Matagorda bay system.

In the developmental stages for the initial WMP, LCRA entered into a memorandum of understanding with TPWD and agreed to work cooperatively in developing the plan with a "...goal of maintaining and, where reasonably possible, improving fish and wildlife resources in the lower Colorado River basin." Instream flow studies on six stream segments (five below the Highland Lakes and one above) were completed in 1992, and these results formed the basis for instream flow targets incorporated into the WMP. LCRA's WMP is subject to amendment as projected water demands in the basin change or new information is developed and, in fact, has been amended several times.

The current WMP, approved by Texas Natural Resource Conservation Commission in 1999, requires LCRA to make releases of stored water to maintain certain instream flows at several control points downstream of the Highland Lakes system to the extent that these flows are not met from other sources of water, such as lateral downstream inflows or return flows, or flows passed downstream to meet customer demands or senior water rights' demands. The level of instream flows to be maintained by LCRA is based on the January 1 combined storage of the two lakes, and the total firm supply required to be released is limited in times of severe drought under the WMP.

### **3.6.2 Bays and Estuaries**

Also, in its consideration of an application for a permit to store, take, or divert water, the TCEQ must assess the effects, if any, of the issuance of the permit on the bays and estuaries of Texas. For permits issued within an area that is 200 river miles of the coast, which commences from the mouth of the river thence inland, the Commission must include in the permit "...to the extent practicable, when considering all public interests...." those conditions considered necessary to maintain beneficial freshwater inflows to any affected bay and estuary system [Texas Water Code §11.147(b)].

Section 16.058 of the Texas Water Code provides for studies designed to identify appropriate freshwater inflows for the bays and estuaries. The TPWD, TWDB, and TCEQ have been conducting studies designed to identify appropriate freshwater inflows for Texas' estuaries since 1977. To date, studies have been completed on the seven major estuaries (Sabine-Neches, Trinity-San Jacinto, Colorado-Lavaca, San Antonio-Guadalupe, Mission-Aransas, Nueces, and the Laguna Madre). Studies are currently in progress for several minor estuaries. The recommendations resulting from these studies are considered by the TCEQ when making water rights permitting decisions.

Section 16.1331 of the Water Code provides that 5% of the annual firm yield of any reservoir and associated works on which construction began on or after September 1, 1985, which is constructed with state financial participation, and which is located within 200 river miles from the coast, be appropriated to the TPWD and its successors for use in assuring adequate freshwater inflows to the bays and estuaries and instream uses. This 5% figure is not necessarily representative of freshwater inflow needs, and additional amounts may be provided by placing conditions in the new permits, if necessary.

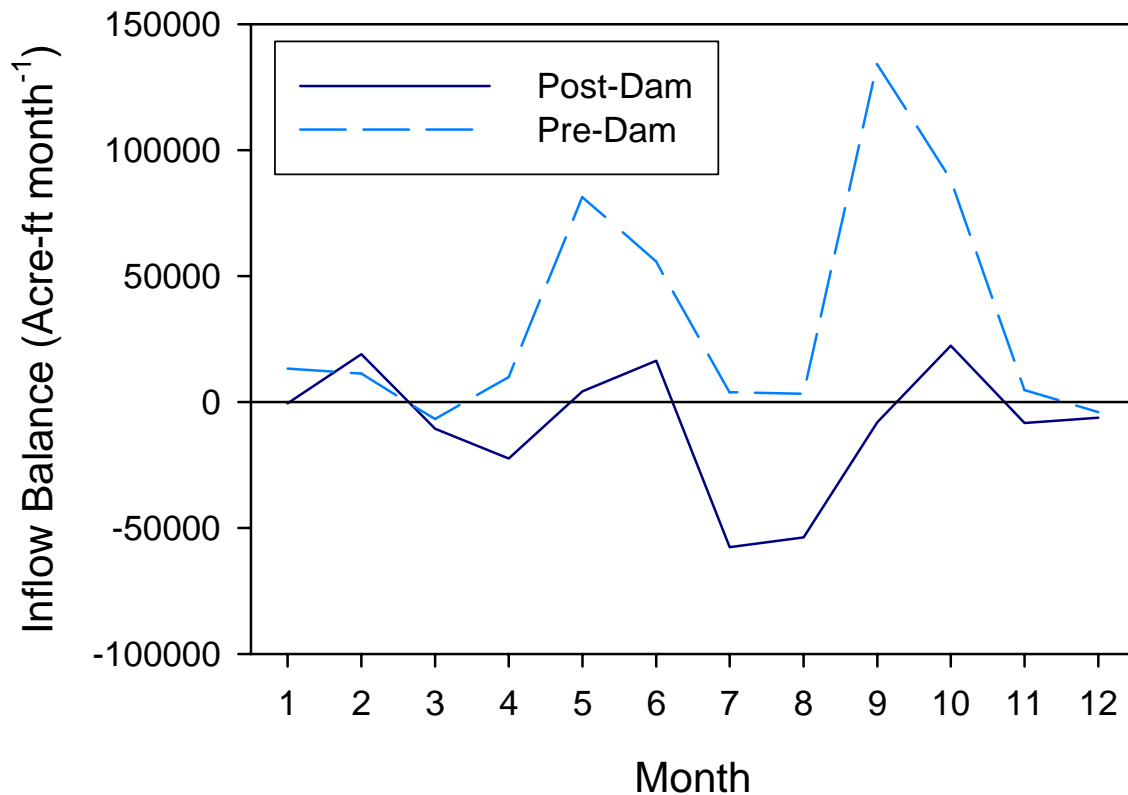
Examples of existing water rights in which there are special provisions for protecting freshwater inflows to bays and estuaries are described in the following sections.

### **3.6.2.1 Nueces Estuary**

There are two major reservoirs in the Nueces Basin that are operated as a system for supplying water to the city of Corpus Christi. Lake Corpus Christi was constructed on the lower Nueces River in 1958, and Choke Canyon Reservoir on the Frio River was completed in 1982. A special condition in the permit to build the new reservoir required the city to provide 151,000 acre-feet of water per year to the Nueces estuary to maintain ecological health related to living marine resources. The inflow requirement was based on what was thought to be available by return flows and flows that could not be captured by the reservoir system. It was not until 1987 that inundation and filling of Choke Canyon Reservoir took place, and the Nueces estuary experienced reduced freshwater inflows throughout the 1990s. The estuarine system has changed dramatically, because prior to 1982, there were two seasonal peak inflow events, and monthly inflows were generally positive; but since 1982 they have been negative (Figure 3–3). Historically, Nueces Bay supported populations of shrimp and oysters, which generally require salinities in the range of 10–20 parts per thousand (ppt). Salinities increased to hypersaline conditions (> 36 ppt) during the drought period of 1988–1990, and consequently reduced the shrimp and oyster populations.

Following a complaint filed by a group called the Coalition About Restoration of Estuaries, the Texas Water Commission (now TCEQ) undertook a review of the permit's conditions. The Texas Water Commission appointed a technical advisory group, and as part of the group's efforts, the TWDB ran a preliminary application of the Texas Estuarine Mathematical Program (TEXEMP) for the Nueces Estuary. This analysis did not include an assessment of nutrient or sediment needs. The results of this optimization analysis indicated that fisheries harvest could be maintained near the mean historical levels observed in the Nueces Estuary with a minimum inflow of 97,270 acre-feet per year, a maximum inflow of 180,600 acre-feet per year, and an optimum inflow of 138,360 acre-feet per year for maximum harvest performance.

In 1992, the Nueces Estuary Advisory Council was created to provide oversight of the releases, monitor the operating plan, and make recommendations for improving the plan. In addition, an interim agreed order was issued by the Texas Water Commission which included target minimum monthly inflows to mimic natural hydrographic conditions in the Nueces Basin. While the annual inflow target was set at 151,000 acre-feet per year, an amount equal to 97,000 acre-feet per year was to be delivered to Nueces Bay and/or Rincon Bayou area. This 97,000 acre-feet per year minimum is derived from the original inflow amount found in the permit that authorizes Choke Canyon—151,000 acre-feet per year—minus the assumed amount of return flows—54,000 acre-feet per year—that are delivered to Corpus Christi Bay and surrounding estuaries, other than Nueces Bay and the Nueces Delta and corresponded favorably with TWDB's application of the TXEMP model.



**FIGURE 3-3 AVERAGE MONTHLY NET INFLOWS TO NUECES ESTUARY BEFORE (1947–1981) AND AFTER (1982–1999) CONSTRUCTION OF CHOKE CANYON RESERVOIR**

If there are inflows to the reservoirs, the city is required to pass through the target amounts. The inflow targets to the estuary can be met by rain, river inflow, return flows and/or flow diversions, as well as spills and releases from the reservoir system. Runoff meeting lawful discharge standards which are intentionally diverted to the upper Nueces Delta region are also credited toward the total inflow amount. Releases from the reservoirs are made at the end of a month if it is projected that the target flow will not be met by these other sources, but passage of inflow necessary to meet the monthly targeted allocation may be distributed over the calendar month. However, at no time is the city required to release water from system storage to satisfy the estuary target inflow amount if insufficient flows enter the reservoirs. A tiered approach was applied to the system, which calls for a target of Max H (Maximum Harvest) when the reservoir system storage capacity is above 70%; a target of Min Q (Minimum Flow that meets all model constraints) when the system storage capacity is greater than 40%, but less than 70%; a critical flow target (1,200 acre-feet/month) when the system storage capacity is greater than 30%, but less than 40%; and a total suspension of the pass-through of inflows to the reservoirs when the system storage capacity is below 30% and the city has implemented certain specific mandatory drought contingency measures.

In April 2001, the order was amended again. The city implemented a freshwater diversion project that diverted water from the Nueces River to the upper reaches of Rincon Bayou to flood the Nueces delta marsh in exchange for modifications in the drought management rules and an increase of 3,000 acre-feet of firm yield from the reservoir system. The Nueces River overflow channel was dug to a depth of 1.0 feet above mean sea level in October 2001 to increase opportunities for inflow into Rincon Bayou. In addition, a pipeline will be constructed that can deliver up to 3,000 acre-feet of freshwater per month from the Calallen Pool on the river to Rincon Bayou. Although the quantity of inflow to the marsh is not up to historical levels, the timing of seasonal peak flows has been restored with consequent increases in productivity of marsh plants and invertebrates that use it as habitat.

### **3.6.2.2 Lavaca-Navidad Estuary**

In 1972, the Texas Water Rights Commission granted a water right permit to the Lavaca-Navidad River Authority (LNRA) that authorized the construction and operation of Lake Texana on the Navidad River. The Navidad River is a tributary of the Lavaca River, which provides freshwater inflow to Lavaca Bay. A partnership was formed between the LNRA, the TWDB and the U. S. Bureau of Reclamation to finance and construct the Lake Texana project. A condition included in the water right permit stated that until the TWDB had provided for the sale and/or use of all of the project water, upon proper application and order, unused waters could be released for any beneficial purpose, including for research purposes in the Lavaca-Matagorda bay system. Lavaca Bay and Matagorda Bay are interconnected, but Matagorda Bay receives most of its freshwater inflow from the Colorado River.

In 1985, and following the final adjudication of water rights in the Lavaca-Navidad Basin in 1981, the Commission amended the Lake Texana certificate to include a provision for "...the release of water for the maintenance of the Lavaca-Matagorda Bay and Estuary System." Through a joint effort by the LNRA, TWDB, TPWD, and the Sierra Club, consensus was reached on reservoir operating guidelines that would provide freshwater inflows to the receiving estuary. Permit holders agreed to a 2-tiered approach requiring: (1) the passage of reservoir inflows up to a prescribed amount each month based on historical median or mean inflow values, depending on the month, when the reservoir storage capacity is greater than 78.18% of its authorized conservation storage capacity; and (2) the passage of the median flow based on the drought of record (5.0 cfs) when the reservoir storage falls below 78.18%.

### **3.6.2.3 Trinity-San Jacinto Estuary**

In 1996, following the Corps of Engineers' settlement of all challenges to the Wallisville Lake Project on the lower Trinity River, the Galveston Bay Foundation entered into discussions with the City of Houston and the Trinity River Authority regarding the requirements for freshwater inflows to the Trinity-San Jacinto estuarine system and Galveston Bay. This effort resulted in the creation of the Galveston Bay Freshwater Inflow Group (GBFIG), which was composed of stakeholders and special interests that had expressed concerns about the continued health of the estuarine system. At the outset, the group established a goal to "Develop a process that will lead to resolution of concerns about freshwater inflows to Galveston Bay." In subsequent meetings, the group reached agreement on the following mission statement: "To reach consensus among stakeholders on an evolving process to develop a scientifically-based management plan and

implementation strategies that will provide freshwater inflows to maintain an ecologically sound environment for the Galveston Bay System.”

In its final recommendation in 2001, the TPWD recommended “...a target inflow within the range from Min Q (4.16 million acre-feet/year) to Max H (5.22 million acre-feet/year).” These inflow values, along with two additional targets (Min Q-Salinity and Minimum Historic), formed the basis for recommendations to the Regional Planning Group for inclusion in its Regional Water Plan. While no specific management strategies were recommended, the GBFIG did suggest targets for minimum frequencies of occurrence for each of the inflow values.

In light of recent concerns raised with the state’s freshwater inflow study for the Trinity-San Jacinto estuary, the TWDB, TPWD, and TCEQ have initiated a stakeholder process to review the study, gather any new information pertinent to the study, and incorporate any changes that are supported by sound science.

#### **3.6.2.4 Colorado Estuary**

Along with the instream flow study discussed earlier, the LCRA’s WMP also addresses freshwater inflow needs. In 1993, the LCRA entered into a cooperative agreement with the TWDB, TPWD, and the Texas Natural Resource Conservation Commission (now the TCEQ) to expedite the freshwater inflow study of the Lavaca-Matagorda bay system. The study was largely a collaborative effort among the cooperating agencies, although the majority of data analysis and modeling was performed by the LCRA. This effort was a significant departure from the other estuarine studies since the LCRA relied heavily on the TPWD’s coastal fisheries database to develop the fishery regression equations, rather than harvest data. That study was completed in December 1997, and resulted in recommendations for two levels of inflow needs: Target and Critical.

To the extent of actual inflows to the Highland Lakes, the LCRA agreed to release stored water for purposes of providing monthly estuarine inflows to the Lavaca-Matagorda bay system at Target inflow levels when the combined storage in Lakes Travis and Buchanan at the beginning of each calendar year (January 1) is greater than or equal to 80% of the water conservation storage capacity of the two reservoirs. If the combined storage in the lakes is less than 80% of their conservation storage capacity, LCRA agreed to release stored water for purposes of providing monthly estuarine inflows at the Critical inflow levels to the extent of inflows each month to the Highland Lakes. The amount of inflows that must be provided from Lakes Buchanan and Travis depend on the monthly rainfall, river inflow, and return flows present as measured near Bay City and like the instream flow requirements, the total firm supply required to be released is limited in times of severe drought under the WMP. These freshwater inflow requirements now are being reassessed and updated to incorporate additional data studies of the estuarine system since the redirection of the mouth of the Colorado River in 1992.

### **3.7 Water Rights Enforcement**

Protecting water rights is a critical issue when water shortages occur. While TCEQ has the authority to enforce water rights by seeking civil penalties for violation of the water rights laws of this state [Texas Water Code §§ 11.081–11.082], the agency has historically relied upon an honor system for protection of water rights in most basins. In a few basins, TCEQ employs a

watermaster to allocate water among water right holders, riparian rights, and exempt users.

Under the honor system, water users are expected to comply with the conditions of their water rights without supervision and cooperate with one another as they divert water from the river. Users will need to know what their right allows them to take and then take no more than that amount. One advantage of the honor system is that there is no continuing cost for enforcing the law. Whenever abuses of the system become serious or streamflows fall to very low levels, temporary streamflow monitoring programs can be established. When water is plentiful, the honor system may be all that is needed. Even if a few users pump more than their appropriated volumes, there still will be plenty of water to go around.

In a number of basins, a key disadvantage of the honor system is that water is seldom plentiful. Also, water users have no reliable way to know how much of the water flowing by their property is theirs to divert or impound and how much they must allow to pass to senior water right holders downstream. Without someone hired to perform a detailed investigation, it is hard to know who is following the law. Often in these basins, the TCEQ enforcement efforts can document only unauthorized diversions and diversions above authorized levels. During droughts, the TCEQ typically receives two types of complaints in these basins:

- Upstream junior water right holders are diverting or impounding water that they should be passing to downstream senior water right holders.
- Purchased water that should be flowing from the seller's reservoir to the buyer's downstream diversion point is instead being intercepted by other users in between.

The only effective way to stop these illegal diversions is to set up a streamflow monitoring program. However, this solution is not normally implemented until there is already a water shortage affecting water right holders, and a monitoring program cannot restore water that should have been available but has already been used by someone else. Under the "honor system," no one is permanently in place to monitor river conditions, pumping volumes, and the volume of available water. No one is charged with anticipating water shortages and warning water users in advance. Since perpetual appropriated water rights are property rights, those who hold them could enforce them through private actions in civil courts, though this is seldom pursued given the cost of litigation and expectation that TCEQ will enforce these rights.

A watermaster is an officer appointed by the TCEQ to oversee river conditions and pumping volumes day to day for water users in one or more river basins [Texas Water Code §§11.326 and 11.327; 30 Texas Administrative Code Chapters 303 and 304]. The watermaster has the authority to allocate flows among priority users during water shortages [Texas Water Code §11.327 (b)]. The watermaster for a particular basin or basins works through the local regional office of the TCEQ.

Water users in two areas of South Texas have established TCEQ watermaster programs. The Rio Grande Watermaster coordinates releases from the Amistad and Falcon reservoir system for irrigation, municipal, and industrial uses. The South Texas watermaster serves the Nueces, San Antonio, Guadalupe, and Lavaca River Basins, as well as the adjacent coastal basins. A watermaster program is currently being established in the Concho River Basin.

The watermasters continuously monitor streamflows, reservoir levels, and water use in their respective river basins. Holders of impoundment rights may notify the watermaster when they plan to release water which has been sold to a downstream water right. The watermaster can then monitor usage downstream to ensure that the released water reaches the buyer. Before starting their pump, opening their sluice gate, or starting to divert water in any way, all water users must notify the watermaster regarding how much water (and when) they plan to divert. The watermaster determines whether a diversion will impact water that rightfully belongs to another user. If so, the watermaster notifies the user with junior priority to reduce pumping or, if necessary, to stop pumping altogether. When streamflows diminish, the watermaster allocates available water among the users according to each user's established priority [Texas Water Code §§11.326 and 11.327; 30 Texas Administrative Code Chapters 303 and 304].

The Rio Grande Watermaster Program was established through the courts as part of the adjudication of water rights for the Rio Grande basin from Fort Quitman, Texas to the Gulf of Mexico. Today this program is governed under the Texas Water Code and Chapter 303 of the TCEQ rules.

Under the Water Code, the TCEQ executive director may appoint a watermaster for any "water division" that has been created [Texas Water Code §11.326]. The South Texas Watermaster Program was established in this way. Also, the Water Code provides for the TCEQ to consider establishing a watermaster program in any area if a petition is received from at least 25 water right holders in that area [30 Texas Water Code §§11.451–11.458]. Such a petition was received for the Concho River basin. The petition was subject to a contested case hearing, where evidence was presented by the petitioners and by protestors, as well as by the TCEQ staff. This petition was approved by the TCEQ on August 11, 2004.

By law, appropriated water right holders in the area served by a watermaster pay the costs associated with the program. These costs are paid through an annual fee [Texas Water Code §11.329]. In addition to the cost of the watermaster program itself, most users are required to add a meter to their pumps or other diversion facilities [30 Texas Administrative Code §§303.11(e) and 304.13]. Depending on the specific technology, a meter may cost \$400 or more. On the other hand, metering the water flow sometimes leads to a savings in pumping costs.

### **3.8 Texas Water Bank/Trust**

The 73rd Texas Legislature created the Texas Water Bank as a mechanism to allow for and assist in the voluntary transfer of water rights between willing buyers and sellers. The transfer may be either temporary or permanent, and in most instances, will require a permit modification from the TCEQ. The Bank is administered by the TWDB, which facilitates the marketing and transfer of water and water rights by providing information regarding the availability of and need for water throughout the state. Rules adopted by the TWDB for the operation of the Bank [Texas Administrative Code Chapter 359] are available via the Internet at the TWDB's Web site.

The 75th Texas Legislature (Senate Bill 1) created the Texas Water Trust as a program within the Texas Water Bank to encourage water right owners to dedicate their water for environmental needs, including instream flows, water quality, fish and wildlife habitat, or bay and estuary inflows. Rules regarding the Water Bank [Texas Administrative Code §359.15] also address the



general requirements for placing water rights in the Water Trust. The Trust offers a significant opportunity to acquire, by donation, lease, or purchase, water rights for environmental purposes in accordance with the statute. It allows unused water rights to be assigned to the Trust, and not used for their authorized purpose, for a specified term without the threat of cancellation.

An owner of a water right may place its water right in the Water Trust to help preserve aquatic life and habitat and ensure their continued availability for future generations. This process involves the following steps:

1. Notification of the TWDB to relate the details of the existing water right and conditions for placing it in the Water Trust.
2. Interaction with the TPWD for the purpose of establishing a manager for and the specific details of the Trust contract for acquiring the water right.
3. Filing of permit amendment documents with the TCEQ to add (or change) the purpose of use designation for the water right from its authorized use to environmental flows.
4. Transfer of the water right permit to the Trust in accordance with the Trust contract and the conditions of the TCEQ's approval.

The TWDB currently waives all fees for deposits to the Water Trust, although the other agencies involved in the process may or may not.

While a basic legal framework exists in the form of the Texas Water Trust, environmental water transactions have been slow to develop within Texas. The Texas Water Trust was established to receive donations of water rights for instream flows. While the opportunity exists, Texas is realizing, like many other states and organizations, that the market for donations is limited. Since it was established in 1997, the Texas Water Trust has only received one donation, in November 2003, consisting of two water rights (1,236 acre-feet/year total) from a private landowner in Hudspeth County.

### **3.9 Other Environmental Flow Programs**

Regulation of water rights is a matter solely within the province of state law. However, in a few instances, federal regulatory programs may impact one's ability to exercise the water rights due to the impact of the regulated activities on environmental flows. The Federal Water Pollution Control Act (Clean Water Act) of 1972, as amended, provides for the permitting of activities involving dredged or fill material in the "nation's waters" (Section 404). This program, administered by the Secretary of the Army, acting through the Corps of Engineers, may issue permits for the discharge of dredged or fill material into navigable waters at specified disposal sites. When issuing such permits, the Corps may include conditions designed to avoid, minimize, and/or compensate (mitigate) for environmental impacts that would result from the permitted activity. Compensatory measures included in the Section 404 permit have, at times, included the establishment of environmental flow provisions.

In 1973, Congress passed the Endangered Species Act (ESA) to “...provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved, to provide a program for the conservation of such endangered species and threatened species, and to take such steps as may be appropriate to achieve the purposes of treaties and conventions set forth....” in the Act. The U.S. Fish and Wildlife Service, the Department of the Interior, and the National Oceanic and Atmospheric Administration, Department of Commerce, share responsibility for the administration of the ESA. Protection for threatened and endangered species under the ESA generally takes the form of designating critical habitat, using the best scientific data available, and taking into consideration the economic impact, and any other relevant effects, that might occur with the designation. In the case of aquatic species, the critical habitat designation may include environmental flow conditions necessary to maintain the aerial extent of a particular habitat, or conditions necessary to accomplish a successful migration or spawn by the species.

The Federal Energy Regulatory Commission (FERC) is an independent agency that regulates hydropower projects. Responsibilities of the agency for private, municipal, and state hydroelectric facilities include: (1) issuance of licenses for construction of new projects; (2) relicensing of existing facilities; and (3) oversight of all ongoing project operations, including dam safety inspections and environmental monitoring. Similar to the Corps of Engineers’ authority with respect to Section 404 permitting, FERC may condition licenses to reduce and/or mitigate anticipated environmental impacts. The relicensing of some facilities in Texas has included provisions for the passage of reservoir inflows to minimize the effects of the facility’s operation on downstream riverine habitats.

## 4. TEXAS AQUATIC BIOLOGICAL RESOURCES

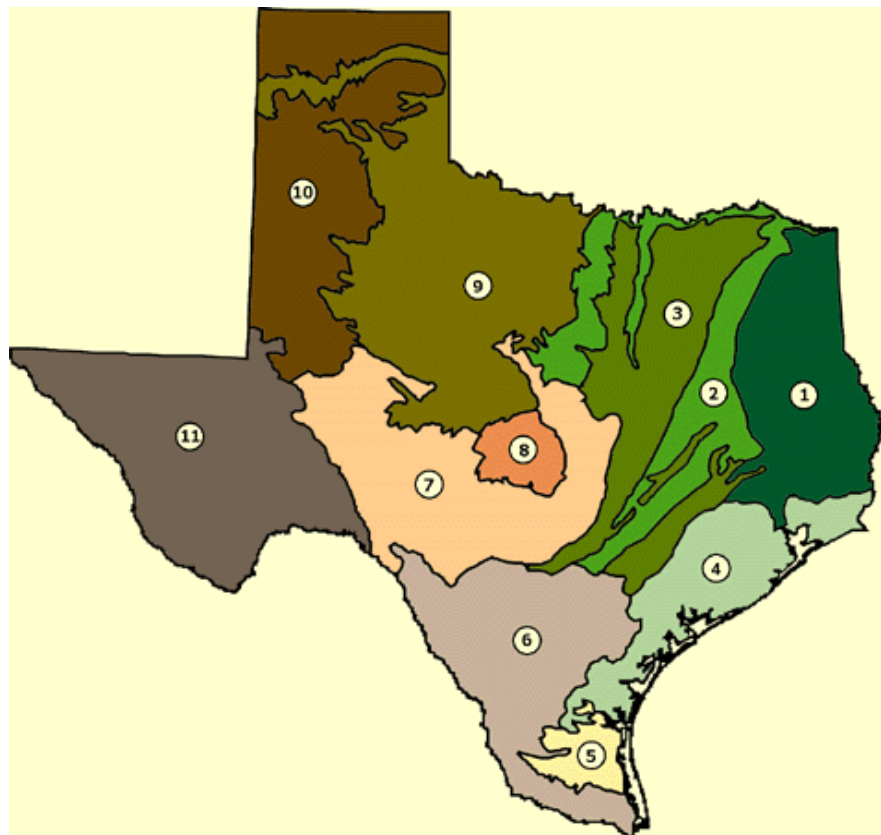
### 4.1 Overview

#### 4.1.1 Ecological Setting

Texas is one of the most diverse states in the United States due to its size and location. As summarized in Texas Environmental Profiles ([www.texasep.org/html/lnd/lnd\\_1reg.html](http://www.texasep.org/html/lnd/lnd_1reg.html)):

*Texas is a large land area covering approximately 261,914 square miles (if you include water area, there are 267,277 square miles). The state is located at a geographic crossroads where many of the major regions of the United States come together: the coastal prairies, the Mexican sub-tropics, the southeastern pinewoods, the central hardwoods, the Great Plains, and the southwestern desert. This accounts for the tremendous climatic and geographic diversity of the state. Texas has 10 climatic regions, 14 soil regions, and 11 distinct ecological regions [Figure 4-1]. These ecological regions of the state represent differences in soils, topography, geology, rainfall, and plant and animal communities.*

- REGIONS**
1. Piney Woods
  2. Oak Woods and Prairies
  3. Blackland Prairies
  4. Gulf Coast Prairies and Marshes
  5. Coastal Sand Plains
  6. South Texas Brush Country
  7. Edwards Plateau
  8. Llano Uplift
  9. Rolling Plains
  10. High Plains
  11. Trans Pecos



**FIGURE 4-1 ECOLOGICAL REGIONS OF TEXAS**

Texas is a state dominated by a system of rivers and streams emptying into a series of coastal estuaries. The Texas landscape has been continually sculpted by its 15 major river networks that course along 191,000 miles of streambed and included in that 191,000 miles are many unnamed streams and over 11,000 named streams and tributaries. Excepting the Canadian, Red, and Rio Grande, the headwaters and major drainages of these rivers are almost entirely within the state. All but four rivers, the Canadian, Red, Sulfur, and Cypress, eventually drain into one of the seven major estuaries, or several associated minor ones, that line the margin of Texas' 400 miles of coastline.

The State is underlain by a system of seven major and sixteen minor aquifers. The influence of the State's aquifers has been subtle and often unrecognized, except for the unique and spectacular expression of the Edwards Aquifer, as seen at Comal and San Marcos Springs and to a lesser degree in approximately 200 remaining springs with significant flow.

#### 4.1.2 Biodiversity in Texas

The diversity of Texas plants and animals reflect its landscape. With some 6,273 species, Texas ranks second (California is first) in overall diversity, according to NatureServe (Stein, 2002). There are a number of these species (340) unique to Texas, ranking the state third in endemic species. Of the 1,245 vertebrate species (fish, amphibians, reptiles, birds, and mammals), 126 are found nowhere else in the world. Texas has more bird species (620) than any other state. Texas ranks second in plant and mammal diversity, first in bird and reptile diversity, fifth in amphibian, and twelfth in diversity of fish species. Texas is one of the fastest growing states in the USA. Biodiversity of the State has been adversely affected as the landscape has been modified to meet agricultural and industrial needs and a rapidly expanding population. Almost half of the State's original wildlife habitat has been converted to other uses. In its report on biodiversity, NatureServe (Stein 2002), concluded that the rate of species extinctions in Texas (Figure 4-2) was fourth highest of all states, with 27 species extinct, three species presumed extinct, and 24 species possibly extinct. Aquatic species are prominent in this listing.

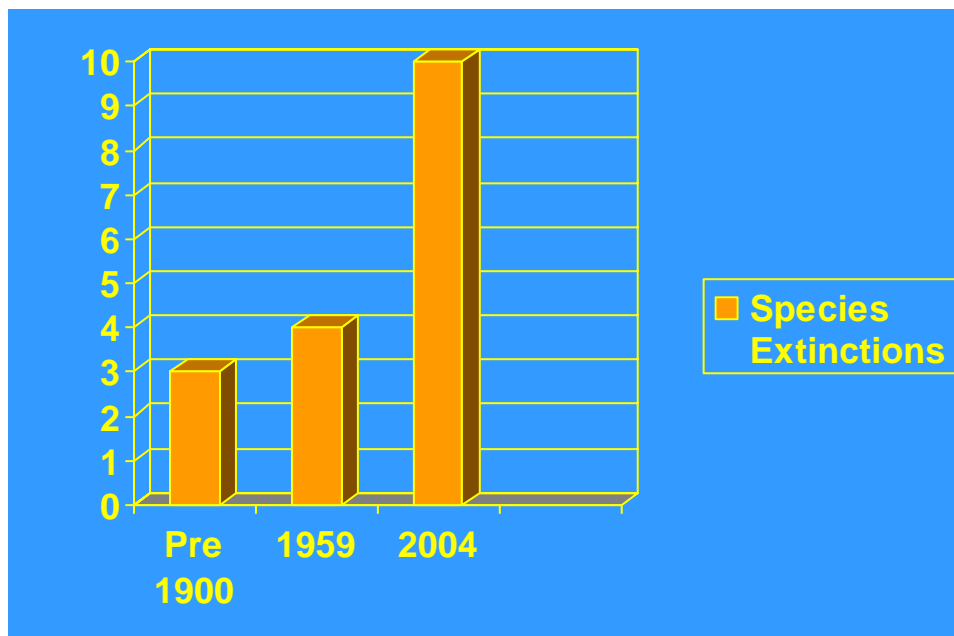


FIGURE 4-2 RATE OF EXTINCTIONS IN TEXAS

## **4.2 Rivers and Streams**

Streams and smaller rivers can be wholly within a province or ecoregion, have unique flora and fauna, and be more similar to stream ecosystems in adjacent watersheds than to a river system in a different portion of the State. All Texas streams and rivers are part of an erosional landscape that provides sediment and nutrient inputs. Nutrient inputs to rivers involve the interaction between simple nutrient cycling and continuous downstream transport, a process called nutrient spiraling. Nutrient enrichment occurs when the rate of nutrient supply stimulates excessive plant production in the watercourse, frequently resulting when fertilizers or organic wastes are discharged into the stream from the watershed.

Collectively, Texas' rivers and streams are biologically diverse. Riparian areas vary widely, with those in eastern Texas typically having extensive bottomland hardwoods and those in northern Texas prairie streams having vast floodplains. Streams and rivers provide habitat for more than 250 species of fish, of which more than 150 are native freshwater species (Hubbs et al. 1991). Native fish communities consist entirely of warmwater species, and their diversity reflects transitions from a Mississippi Valley fauna to the north and east, to a Rio Grande fauna to the south and west (Conner and Suttkus 1986). Consequently, East Texas rivers have diverse communities, while rivers in West Texas are more depauperate (Edwards et al. 1989; Linam et al. 2002).

The native stream fish fauna in Texas includes mainly cyprinids (minnows), percids (darters and perches), catostomids (suckers), centrarchids (sunfishes and basses), ictalurids (catfishes), and nearly 20 other families. Over 50 species of unionid mussels are found in Texas, inhabiting rivers, streams, canals, reservoirs, lakes, and ponds (Howells et al. 1996). Mussel populations in Texas are commercially valuable (shell harvesting) yet little studied. Habitat modification, pollution, commercial harvesting, and the introduction of exotic mussels threaten native freshwater mussels (Howells et al. 1996). Aquatic macroinvertebrates in Texas streams are incredibly diverse, but this fauna remains largely undocumented. It is possible that the number of species of aquatic invertebrates occurring throughout Texas numbers in the thousands.

In addition, the biogeographic origins of the faunal elements found in Texas streams are equally diverse, with representatives being known from the Gulf Coastal Plain, Chihuahuan Desert, Great Plains, and the Neotropics. Similar to the fishes, macroinvertebrate diversity and densities are higher in eastern Texas when compared to those of the western portion of the State. Anadromous organisms (e.g., river shrimp or "prawn") may travel far upstream into rivers, streams, and spring systems to complete their life cycle (Bowles et al. 2000). Texas also has its share of nonnative species that inhabit aquatic environments. The most problematic of these include riparian, submerged, and floating plants, snails, mussels, clams, fish, and mammals.

### **4.2.1 Riverine Effects on Ecosystems**

Stream ecologists are convinced that streams and rivers require dynamic flow regimes in order to keep riverine ecosystems functioning. The importance of a dynamic flow regime is based on observations that different components of the regime perform different tasks within the system. The base flow, which normally is composed of groundwater and return flow, keeps the various instream habitats inundated, maintains continuous transport of some sediments and nutrients, causes oxygenation of the water, and keeps assimilation of wastes from both riverine and

anthropogenic sources ongoing. Stormwater runoff and the associated high flows add to the diversity of aquatic habitats utilized by fishes, mussels, invertebrates, plants, etc.; maintain river channels by moving sands, gravels, and larger sediments; and prevent the proliferation of aquatic plants that can choke the channel and prevent terrestrial plants from encroaching into the river bed. Higher flood flows move great amounts of sediment and can alter the channel through fluvial processes; provide large organic inputs from the watershed, and further prevent terrestrial vegetation from encroaching into the river channel. High flows are often the stimulus for fish spawning and migrations and can cause a number of other biological processes to occur. Flows that inundate the floodplain sustain hardwood bottomlands and many other types of wetlands. This connection between the floodplain and river channel replenishes riparian and bayou fish and wildlife populations, maintains valuable forest resources, and provides exceptional fish and wildlife habitats after the flows have receded.

Recognition of the need for a continuous and adequate dynamic flow regime within Texas streams and rivers, along with implementation strategies, provides the lowest risk that impaired ecosystem conditions will not occur in the future. Streams and rivers provide the final processing and treatments of effluents and pollutants. If an inadequate normal flow regime is made worse by a severe drought and the anthropogenic inputs exceed the assimilative capacity of the river, then the impaired condition could cause loss of biodiversity, human health concerns, loss of recreational uses and aesthetics, and a substantial increase in the time and costs of recovery.

#### **4.2.2 Riverine Environmental Indicators**

Since an instream flow study is largely a fish and wildlife resource evaluation, the indicators used to judge the adequacy of environmental flows should be based on measures related to the maintenance or restoration of fish and wildlife resources. Conserving biodiversity and maintaining biological integrity, as discussed in the Texas Instream Flow Program documents, are important elements for meeting the goal of a sound ecological environment in Texas rivers and streams. An example indicator is the Index of Biotic Integrity (IBI), which is based on multiple attributes of the resident fish community. TPWD has developed a regionalized IBI applicable to wadeable streams across the State that is currently used by TCEQ.

Conservation of biodiversity is important since communities of aquatic organisms that are diverse are resilient to impacts caused by natural and human-induced system changes. There are many indicators of diversity, such as diversity indices and the presence of rare, at-risk, sensitive, specialized, or indicator species such as freshwater mussels. An important element of conserving biodiversity involves conserving diverse habitats in rivers and streams. Because diverse habitat is supported by variable, natural flow regimes, it is important to ensure that the natural fluctuations in streamflows are maintained seasonally and between years. An indicator of flow variation and alteration is The Nature Conservancy's Indicators of Hydrologic Alteration (IHA). Using IHA, the Conservancy has developed a method, the Range of Variability Approach, to derive patterns of flow that maintain the natural range of variability.

#### **4.3 Bays and Estuaries**

The diverse ecological character of the seven major (Figure 1-2) and several minor estuarine systems that line the Texas coast are defined by a climatic gradient that exhibits decreasing precipitation and freshwater inflows from north to south and east to west. Sabine Lake, at the

northern-most extreme, experiences average annual rainfall in excess of 55 inches, freshwater inflows averaging 14.7 million acre-feet, and a salinity range of 4 to 14 parts per thousand. At the southern extreme, the Laguna Madre receives less than 25 inches of rainfall annually, but this is exceeded by evaporation. The Laguna is therefore classified as a hypersaline lagoon, where under normal conditions salinities may range up to 50 ppt, far exceeding seawater. Table 4-1 summarizes general information about Texas estuaries.

**TABLE 4-1 SUMMARY INFORMATION FOR MAJOR TEXAS ESTUARIES**

Bay	Surface Area (acres)	Drainage Area as % of Texas	Drainage Area (sq. miles)	Average Annual Freshwater Inflow (acre-feet)	Average Salinity ppt (a)	Number Of Fish Species (b)
Sabine Lake	60,000	7	18,000	14,000,000	5	115
Galveston Bay	350,000	12	33,000	10,000,000	15	163
Matagorda Bay	270,000	16	44,000	3,100,000	20	181
San Antonio Bay	130,000	4	11,000	2,300,000	15	180
Aransas-Copano Bay	130,000	1	2,700	440,000	15	174
Corpus Christi Bay	120,000	6	17,000	600,000	30	187
Laguna Madre	370,000	4	10,000	610,000	35	192

(a) Orlando, et al, 1993—Average salinities have been rounded to the nearest 5 ppt.

(b) Texas Parks and Wildlife Department Coastal Fisheries monitoring data from 1977 to 1997.

#### 4.3.1 Estuarine Characterizations

**Sabine Lake**, a lagoonal embayment, which encompasses the estuaries of the Neches and Sabine Rivers, is located on the state line with Louisiana, receives the highest inflow per unit volume of the Texas bays, and has abundant freshwater marshes around its periphery. Salinities generally remain low and in many areas promote the growth of plants that thrive in freshwater. The Salt Bayou marsh complex, where ducks, juvenile shrimp, and fish thrive, contains over 60,000 acres of valuable habitat. Many of these intermediate marshes in the Sabine Lake system have been damaged or lost due to saltwater intrusion resulting from ship channels, brine disposal from historic oilfield exploration and production, and relative sea level rise. Extensive marsh restoration efforts are ongoing around Sabine Lake. The pending deepening and widening of the Sabine-Neches Waterway and continuing relative sea level rise will result in more saltwater entering the bay from the Gulf with unknown consequences to the health of the bay and its freshwater marshes.

**Galveston Bay**, to the west of Sabine Lake, is Texas' largest bay system, and is the estuary of the Trinity and San Jacinto Rivers, as well as several smaller coastal streams. Over 10% of Texas

drains into this bay, but about 46% of the state's population lives in its drainage area. Galveston Bay, like Sabine Lake, has experienced increased salinity levels due to channelization. It has also suffered the greatest level of subsidence on the Texas coast, exceeding 10 feet in some areas. Changing salinities impacts one of Galveston Bay's most important habitats, oyster reefs. The extensive oyster reefs provide shelter and cover for many small fish and crabs that are important parts of the food chain. Oysters filter the water and in some cases the reefs are so extensive they affect circulation patterns in the bay. Water that is too salty allows diseases and predators of oysters to thrive. There are extensive efforts to restore these brackish marshes.

***Brazos and San Bernard Rivers*** lie between Galveston Bay and Matagorda Bay and flow to the coast without passing through typical open-water bay systems. However, both of these rivers have extensive estuaries, and as they flood and subside, they feed a substantial network of cordgrass marshes and hardwood bottomland wetlands around the Freeport area.

***Matagorda Bay***, is the second largest bay system in Texas and includes the estuaries of the Lavaca and Colorado Rivers. It represents the beginning of a transition from the upper coast with precipitation excess (over evaporation) to the lower coast with evaporative deficit, and a transition from fresher, muddy-bottom bays dominated by extensive cordgrass and freshwater marshes in the east, to saltier bays with more seagrasses to the west. Like Galveston Bay and Sabine Lake, salinities in Matagorda Bay have been increased due to the deep-draft ship channel. A small part of the estuary in Lavaca Bay is closed to fishing because of mercury contamination that has accumulated of fish and shellfish, but remediation efforts have been undertaken that should restore fishing in the region. The Colorado River historically emptied into the Gulf of Mexico, but in 1992 was diverted into the Bay to provide freshwater inflows to benefit the eastern arm of Matagorda Bay.

***San Antonio Bay***, which is the estuary of the San Antonio and Guadalupe Rivers, receives about the same amount of inflow per unit volume as the Galveston Bay system, but does not have a direct connection to the sea, so it tends to be much more responsive to variations in inflow. Consequently, San Antonio Bay can be completely fresh at times after a large flood event, or become hypersaline during a prolonged drought. Oyster reefs are extensive in San Antonio Bay, and the region is famous for supporting whooping cranes in the Aransas National Wildlife Refuge. Cedar Bayou, the closest inlet to the sea, is usually closed, but has intermittently been opened in the past.

***Aransas Bay***, the estuary of the Mission and Aransas Rivers, is unique in Texas because the Mission and Aransas Rivers that are the sources of inflow to the estuary drain small coastal watersheds that are sparsely populated. Consequently, the system is probably the least modified of all Texas estuaries. The Aransas Bay system has much less inflow than San Antonio Bay or Matagorda Bay. Copano Bay, the secondary bay in the system, is dominated by oyster reefs in the center and marshes surrounding the bay. Aransas Bay is dominated by muddy sediments in the open bays, but has extensive seagrass beds surrounding the bay margins. Black mangrove habitats characterize the southern part of the tidal delta regions of the bay.

***Corpus Christi Bay***, which includes the estuary of the Nueces River, accentuates the transition begun in Matagorda Bay with its evaporative deficit, extensive seagrass beds, and average salinities nearly equal to Gulf waters. Corpus Christi Bay, like Galveston Bay, is an urbanized estuary. Bay systems upcoast from Corpus Christi Bay have experienced significant losses of



marsh habitat while, Corpus Christi Bay has lost most of its oyster reefs. Oyster reefs are no longer an important habitat component in estuaries west and south of Corpus Christi Bay. As freshwater inflow to Nueces Bay has decreased and been diverted from the historic delta marsh, the marsh at times can experience salinities over twice Gulf salinities, with substantial harm to marsh vegetation in the delta.

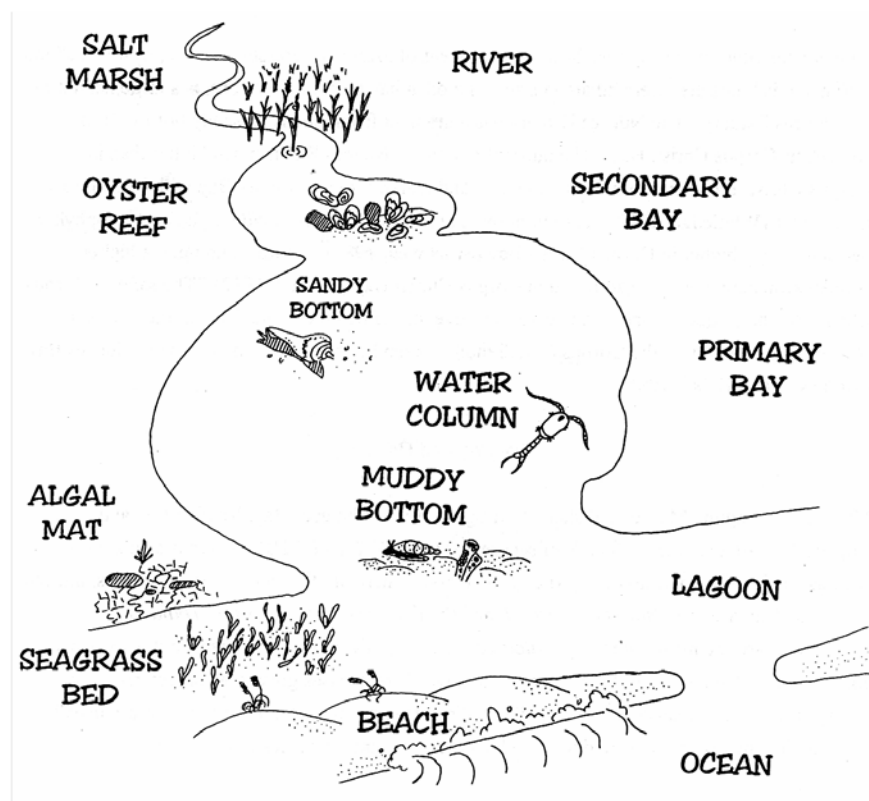
***The Laguna Madre***, the largest major estuarine embayment on the south Texas coast, has nearly half of its sandy bottom covered with seagrasses. Its few direct connections to the Gulf combined with an arid drainage basin and high evaporation rates combine to make the Laguna Madre one of five hypersaline lagoons in the world. The salinities of the Laguna Madre, although relatively high now, commonly reached three times the salt concentration of seawater before the Gulf Intracoastal Waterway and Mansfield Pass were constructed. Extensive wind tidal flats, called the Land Cut, separate upper and lower Laguna Madre. Whereas upper Laguna Madre has little inflow and no direct connection to the sea, lower Laguna Madre has several inlets and larger volumes of return flows. These differences are responsible for the different biological and chemical characteristics of the two segments of the system.

***The Rio Grande***, on the border with Mexico, is the southmost estuary in Texas. Like the Brazos River, the Rio Grande flows directly into the Gulf, rather than into a coastal bay. Regardless, it provides valuable estuarine habitat for over 30 miles of its length that is utilized by shrimp, crabs, and a variety of fish. Reduced flood flows in the lower Rio Grande during the severe drought of the 1990s and early 2000s caused the river to completely lose its connection with the Gulf for extended periods of time in the recent past; however, high flows during 2003 and 2004 have kept the mouth of the river open. During periods when there was no connection to the Gulf, the estuary ceased to exist, and the former estuarine portion of the lower channel became relatively fresh with the continued inflows from the river, even though they were diminished.

#### **4.3.2 Estuarine Habitats**

Estuarine habitats are diverse. Habitats are the elements of an environment that sustain an organism or a specific community of organisms. The populations of different species of organisms living in a habitat are called a “community.” In a Texas bay ecosystem, typical habitats include riverine, salt marsh, algal mat, seagrass bed, water column, open bay bottom, oyster reef, beach, and oceanic habitats (Figure 4-3). Energy can be transferred among habitats by physical movement of the water or by movement of the organisms between habitats. The interactions among habitats are partly responsible for the high productivity that is characteristic of estuaries and the ecological services that benefit mankind.

All Texas estuaries have a common structure similar to that illustrated in Figure 4-3. Ocean water exchange with the Gulf of Mexico occurs through a break in the barrier island called a “pass.” Beach habitat faces the ocean or barrier island. The gulf is connected to a primary bay with a bottom that is predominantly a muddy habitat. There are patchy areas of sandy bottom or oyster reefs. Oyster reef habitats occur mostly in secondary bays or near the junction of primary and secondary bays. Rivers empty into the secondary bays; sometimes there are tertiary bays or lakes associated with rivers. Marshes line the river sources of tertiary and secondary bays. Lagoons run parallel to the barrier islands, and perpendicular to primary bays. Primary bays are connected by the lagoons; therefore, lagoons are important for transport of materials and recruitment between systems. Lagoons are long and narrow, with a short fetch. Furthermore,



**FIGURE 4-3 HABITATS FOUND IN TEXAS ESTUARIES (Montagna et al. 1996)**

lagoons are in the lee of the barrier island. Therefore, the water in a lagoon is salty, calm, and clear, relative to the primary bays, and seagrass beds develop well in this habitat. Algal mats develop on broad, supratidal tidal flats. Seagrass bed habitat is mostly composed of five species, but the thin-bladed shoal grass, *Halodule wrightii*, and the thick-bladed turtle grass, *Thalassia testudinum*, are the most common. *Halodule* grows rapidly in disturbed areas, but is usually out-competed by *Thalassia* over time. The areas in which seagrasses grow are characterized by strong currents and a shallow bottom.

The sediments range from sandy to fine, and are usually reducing just below the surface due to high oxygen consumption rates of decomposer microbes. Seagrass beds support a very diverse and productive food web by providing a source of carbon for the food web and a place for fish and invertebrates to hide from predators. The high amount of biomass from these plants leads to high rates of gross primary productivity and net community productivity. Seagrass is difficult to digest because of structural compounds. However, seagrass is an important contributor to the detrital food web. Seagrass is also a substrate for epiphytic algae (e.g., microalgae that grow on seagrass blades) and animals (e.g., crustaceans and polychaete worms). Seagrass beds serve an important role as nursery grounds for larval fish and invertebrates. They also serve as buffers against storms and can help filter contaminants from the water. Many animals are supported by detritus trapped by the seagrass blades or beneath the sediment. Many kinds of fish live in the seagrass meadows. In winter, a variety of duck species move into the seagrass meadows to feed on small invertebrates or the roots and rhizomes of the seagrass itself. Larger predatory fish,

such as a redfish, black drum, and spotted seatrout feed on the smaller fish and larger invertebrates that congregate in seagrass meadows.

Salt marsh habitats are in intertidal regions of the bay. They are often expansive near a source of fresh water in secondary bays, or fringing wetlands within primary bays. Marshes are dominated by cordgrass, *Spartina alterniflora*. Along the eastern seaboard of the United States, salt marshes extend for many kilometers because of the large tidal range. In contrast, Texas has very small tidal ranges, so salt marshes only extend for a few meters from the shoreline. Marshes are important because they trap sediments, store water, buffer the coast during storms, and filter wastes from water.

Mangroves, such as *Avicennia germinans*, gradually replace salt marsh grasses and form large mangrove swamps in the southern part of Texas. Aransas Bay is near the northern extent of the range for mangroves within the entire continent. Because of mild winters over the last 15 years, mangroves have expanded dramatically, particularly along Redfish Bay. Texas mangroves are more like bushes, rather than the trees that line the shore of Mexico and southern Florida. Mangrove habitat provides all the benefits that marsh habitats provide.

Seagrass, marsh, and mangrove habitats act as sediment and nutrient traps. Beneath the plants are strong reducing conditions, and often low oxygen levels. Because of the high rates of primary production there is a high amount of dead and decaying plant matter, which fuels a detrital food web. This causes biomass of producers and consumers to be high. These vegetated habitats are important nursery and feeding grounds for a variety of invertebrates and fish.

Algal mat habitats are unusual features of the supratidal zone that occur in many locations in Texas estuaries, but especially where there are large expanses of tidal flats. They occur when rain or wave surge collects in low spots near the shore, often in areas behind marshes or mangroves. The trapped water is very shallow, and often becomes quite hot and saline. However, the water also allows a bloom of photosynthetic bacteria, called cyanobacteria, or blue-green algae, that live on the sediment surface. These producers are very important to the bay ecosystem because they have the ability to fix atmospheric nitrogen into a form more usable by other producers and bacteria. When this material gets transported back into the estuaries, it represents a nutrient spike that can enhance primary productivity in the estuary. Aside from cyanobacteria and other microbes, there are not many species that are endemic specifically to the algal mats. Algal mats are important habitats for migrating waterfowl.

Beach habitat occurs in two types. Bay shorelines that are not covered by salt marsh grasses can be considered beaches. However, bay beaches are not as diverse and are not as distinct a habitat as are oceanic beaches. Oceanic beaches are found on the Gulf of Mexico side of barrier islands. While these habitats are not directly connected to estuaries, there is interaction between the estuary and the adjacent beach. Many mobile animals, such as fish and crabs, move freely between the two ecosystems via tidal passes. Because of wind, waves, and tides, a lot of detritus piles up on the beach itself. This detritus is mostly plant material, particularly *Sargassum* seaweed or sea grasses that are transported by tides out of the bay area after storms. While this decomposing matter may smell offensive, and is often cleaned from the beaches by humans, it serves as an important source of food for near coastal environments. In addition, buried debris can trap sand and is partly responsible for the beach accretion process during the summer and pre-hurricane seasons.

The water columns that fill all estuaries are “Pelagic habitats.” Although the water column covers a huge surface area in Texas, it is not very deep, and often only as productive as the bay bottom. Water column productivity is much lower than in vegetated habitats. Typically, in oceanic environments such as the Gulf of Mexico, the water column habitat is very deep, and more productive than the bottom. The water column of bays can become quite turbid as sediment is resuspended by wind or human activities. Because freshwater mixes with salt water in the bays the salinities are typically brackish (10–25 ppt). However, when evaporation exceeds freshwater inflow and flushing by the ocean, salinities can become saltier than the ocean (> 35 ppt). The water column is usually well oxygenated. Mixing, due to the consistent high wind speeds, and shallow depths cause stratification of the bay water column to be a rare event except where mans activities have altered these dynamics. The food web consists of phytoplankton (one celled algae) being eaten by zooplankton, which are in turn eaten by fish. This grazing food web dominates the water column, in contrast to vegetated habitats that are dominated by the detrital food web. Primary production by phytoplankton in estuarine water can be relatively high. In temperate zones, there is a strong seasonal change (the spring and fall blooms), which is not as pronounced near the semi-tropics.

Muddy and sandy bottoms are common habitats beneath the pelagic zones of all Texas bays. Sand can support larger animals that might sink in the soft mud. Sandy bottoms are often accompanied by stronger currents and higher water transparency in comparison with muddy water habitats. Attached algae, such as macroalgae, and benthic diatoms can yield high productivity in sandy bottoms. Because of the clear water, there are also many filter feeders in sandy sediment. A common filter feeder is the quahog clam, *Mercenaria campechiensis*. *Mercenaria* is quite large for a clam, and is capable of removing large amounts of plankton from the water column. The lightning whelk, *Busycon contrarium*,—has a backwards-curving shell—uses the edge of its shell and a rasping radula to feed on large clams, such as *Mercenaria*. Blue crabs, *Callinectes sapidus*, can be found in many habitats, including sandy bottoms. They tend to be opportunistic, eating any animals or detritus that they encounter.

Muddy bottoms are by far the most common benthic habitat in Texas bays, where there is a lack of other physical features, such as grasses or oyster reefs. Movement of the water over the surface of the mud keeps the sediment oxygenated to about one centimeter depth. Below this region is a strongly reduced environment due to the absence of oxygen-generating producers. Mud is easily resuspended, and muddy bottoms may experience erosion or deposition of sediment. Therefore, turbidity tends to be high, which restricts the presence of producers and filter feeders. Deposit feeders, however, can be present in high abundance and diversity. Biomass and metabolism are also relatively high. The muddy bottom ecosystem is driven by two sources of carbon: phytoplankton and detrital matter. The filter feeders may eat phytoplankton in the water column, or detritus that is dissolved in the water. Among the dominant species are small benthic invertebrates, such as clams, polychaete worms, and crustaceans. These animals are important food sources for edible shrimp, *Penaeus* sp. There is, of course, a large commercial shrimp fishery based on these muddy habitats. The small clams are a primary food source for black drum, *Pogonias cromis*. Shrimp are eaten by a diverse assemblage of fish, such as catfish, *Arius felis*; red drum, *Sciaenops ocellatus*; and flounder, *Paralichthys lethostigma*.

Oyster reefs are intertidal or subtidal areas of open bottom that have become covered with the living and dead shells of the oyster, *Crassostrea virginica*. In Texas, oysters flourish in shallow

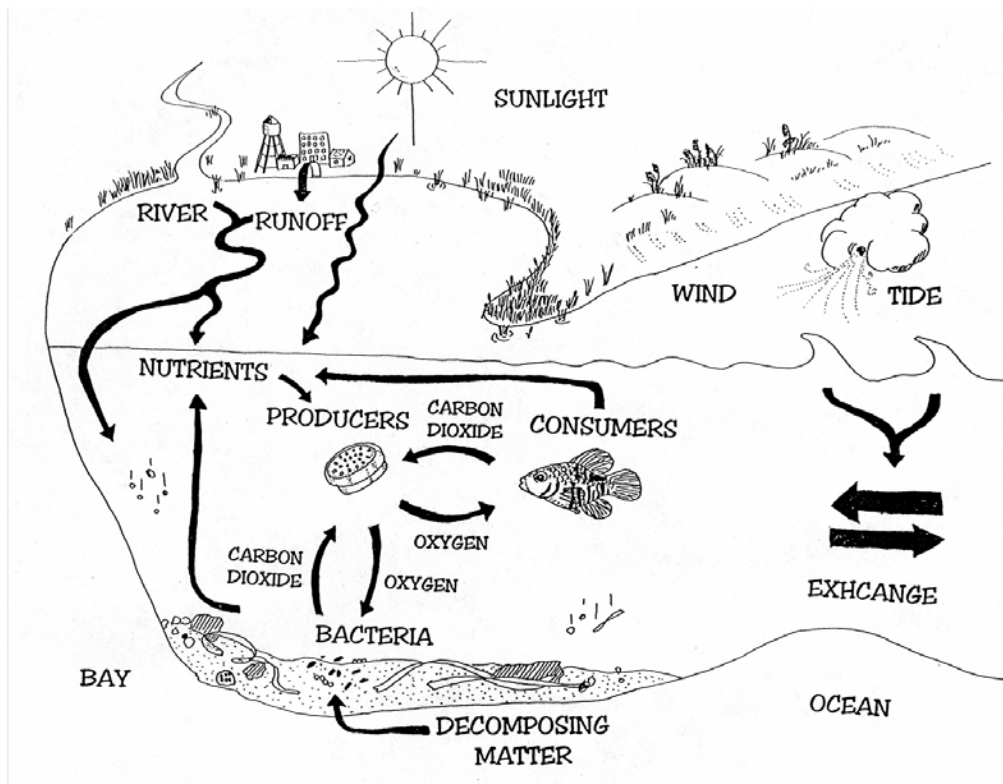
water of intermediate salinity. In secondary bays with high inflow, oysters form extensive reefs. These reefs have two dramatic habitat effects. Both living oysters and dead shells provide a hard substrate for encrusting fauna, one of the only two natural hard-bottom habitats in estuaries of the Texas coast. Furthermore, the physical structure of the reefs acts as a barrier to water flow, which can cause organic matter to settle out of the water on to the reef, where it can fuel a detrital-based food web. Many species in oyster reefs are filter feeders, including the oyster itself and animals that encrust oyster shells. These filter feeders are the natural vacuum cleaners of estuaries and work to maintain the water quality of bays. With such a high biomass and diversity of food sources, several predators can be found in the vicinity of oyster reefs. These include the spider crab, *Libinia dubia*; and stone crab, *Menippe adina*. Stone crabs use their powerful claws to break open oyster and mussel shells, while spider crabs use their long arms to grab smaller prey. Fish also frequent oyster reefs, either to hide among the shells, or to find food. The ubiquitous black drum, *Pogonias cromis*, use their pharyngeal teeth to crush shells of a variety of bivalve mollusks.

The different marine habitats in Texas bays and estuaries are defined by the physical structures, particularly vegetation, which can be found in each habitat (Figure 4-3). Seagrass beds are very diverse and productive, and serve as an important nursery ground for larval fish and invertebrates. Salt marshes are important sources of organic matter, and serve to buffer shorelines. Beach habitats experience high energy from wave impacts, but are still home to several species of animals. The water column refers to pelagic habitat. Water column organisms that are at the mercy of the currents are called plankton. The larger animals, such as fish, that eat plankton, are called nekton. Sandy bottoms occur near shore, and can support large animals. Muddy bottoms are more common, but support smaller animals. Oyster reefs are very diverse, because the oyster shells provide a substrate and home for many different species. Although each habitat may seem distinct, there are many interconnections among the habitats. Water currents, waves, and tides transport organic matter, energy, and animals between habitats. Many types of animals, such as the red drum and blue crab, can move among many different habitats.

### **4.3.3 Estuarine Functions**

Like all ecosystems, the estuarine ecosystem consists of the system itself, its input sources, and output targets (Figure 4-4). The bay area ecosystem receives energy from external sources. The primary source of energy for the bay is the sun. Energy also comes from rivers, groundwater, and terrestrial runoff, which provide nutrients for primary producers and detritus for consumers and mineralizers. Energy is exchanged between the coastal ocean and bay as current, wind and tide movements of nutrients and detritus, and the migration of some consumers, such as fish and shrimp. Energy leaves the bay ecosystem through a heat sink, returns to land through human fishing and hunting, or is transferred to the coastal ocean.

The main structure of the bay system includes six energy sources, seven storage tanks, and three subsystems (Figure 4-4). Sun, wind, tide, river, runoff, and ocean are the energy sources. The storage tanks are salinity, temperature, carbon dioxide (CO<sub>2</sub>), water (H<sub>2</sub>O), nutrients, kinetic energy, oxygen, and detritus. Three main subsystems (i.e., the ecological processes) are: producers, consumers, and mineralizers. All processes require input from sources that are modified by storage systems.



**FIGURE 4-4 ESTUARY ECOSYSTEM COMPONENTS (Montagna et al. 1996)**

#### 4.3.3.1 Sources

Irradiance from the sun increases the temperature of the whole ecosystem, which, in turn, affects the physiology of every producer, consumer, and mineralizer. Sunlight provides the energy for photosynthesis, the biochemical pathway used by almost all producers to increase their biomass, and indirectly gain energy. Heat from the sun also creates wind. Warm air is less dense and tends to rise upward in the atmosphere. Cool air is denser and sinks through the atmosphere. The movements of these parcels of air are known as air currents, or on a more local scale, wind. In the bay ecosystem, wind transfers kinetic energy and oxygen pressure from the air into water. Energy leaves the bay system through sedimentation and subsidence of organic matter, as well. Tides originate from the gravitational forces of the sun and moon. Depending upon many factors, including latitude, weather, and local geography, different places on the planet have different tidal zones (ranging from a few centimeters to tens of meters) and a different number of tides in a day (usually 1 or 2). Tides behave much like large, slow waves; they can transfer kinetic energy and transport nutrients and detritus between the ocean and bay systems. Rivers are indirectly a product of the sun and gravity. River water is the product of precipitation or artesian wells (stored precipitation water). Precipitation results from atmospheric water vapor that is itself the product of evaporation from the ocean. Rivers provide kinetic energy and transport nutrients and detritus from land to the bay ecosystem. Runoff is freshwater that originates from sources other than rivers. Typically, this is drainage from the land directly into the bay. However, we also include non-river sources, such as return flow from a city sewer system, and direct rainfall onto the bay surface. Runoff can transport nutrients and detritus from

land to the bay ecosystem. Finally, the ocean provides energy for the bay ecosystem. Upwelling currents can bring up nutrients and detritus from the sea bottom. Water currents, waves, and tides act to transfer energy between the ocean and bay. Migrating consumers can also transport energy into the bay ecosystem. Typically, the net effect of migrating consumers is to transport energy and nutrients out of the estuary.

#### **4.3.3.2 Storage**

The bay ecosystem has seven main storage tanks (Figure 4-4). Storage tanks in an ecosystem are nonliving things that stand for an energy storage level, or can be transferred into an energy storage level in an ecosystem. The storage tank is passively accumulated or lost due to the effects of energy sources or a living component's processes in the system. Inside a living component, the biomass can be defined as a storage tank that is accumulated or lost due to biological processes.

Temperature storage is a product of solar radiation. Heat is lost through sea water evaporation to air, or conduction to the deep sediment layer. Water loss by evaporation has a cooling effect on any moist surface. Temperature increase may stimulate physiological processes, such as photosynthesis, energy intake, respiration, excretion, natural death, migration, and reproduction.

Salinity is determined by the influences of freshwater from rivers and runoff (0 ppt) and the influence of seawater from the ocean (34–36 ppt). Salinity is also determined by evaporation. Salinity in bays is usually between about 5 and 25 ppt, but can become much lower in times of flooding, or much higher, even saltier than the ocean, in areas or periods of low rainfall. Salinity affects some physiological processes, such as photosynthesis, natural death, respiration, reproduction, excretion, and migration.

Carbon dioxide and water are needed for photosynthesis or chemosynthesis, and are produced by respiration. Photosynthesis and chemosynthesis are biological processes that convert inorganic carbon into organic carbon and produce oxygen. Respiration, on the other hand, consumes oxygen, converts organic carbon into inorganic carbon, and releases energy for cellular functions. By definition, consumers can only respire, but producers both respire and synthesize. Autotrophic production occurs by photosynthesis or chemosynthesis.

Nutrients, such as nitrogen and phosphorous, are also needed by producers. Ammonia, nitrates, and nitrites are sources of dissolved inorganic nitrogen which is needed to construct some organic molecules, particularly proteins and fatty acids. Although much focus in the past has been placed on inorganic nitrogen, increasingly, scientists are finding that input of organic nitrogen from freshwater sources is driving many ecosystem processes. Phosphorus, which comes in the form of phosphates, is important for cell membranes making nucleic acids and in molecules that transfer energy through the tissues. Microbial mineralizers and consumers break down tissue and release nutrients back into the ecosystem, a process called “recycling.”

Kinetic energy originates from wind, river, tide, runoff, and ocean currents. “Kinetic energy” refers to the movement of water in the bay. The higher the kinetic energy of water, the more oxygen and nutrients it is able to contain.

Oxygen is necessary for respiration. Oxygen is used to break down organic carbon bonds to release the energy for use by tissues. The oxygen-carbon molecules that are released as a by-product of respiration are in the form of carbon dioxide. Consumers cannot generate their own oxygen, and must rely on the oxygen generated from producers. Producers generate oxygen through photosynthesis by removing the carbon from carbon dioxide. The carbon is used to form organic molecules such as carbohydrates, proteins, and lipids, while the remaining oxygen is released. The amount of oxygen in the water is affected by physical factors, such as, wind, tide, rivers, and kinetic energy. Oxygen solubility in water is also affected by salinity, temperature, and pressure.

Detritus is nonliving, decomposing organic material, including fresh leaves sloughed from seagrass or marsh grass, fecal matter from animals, and dead animal and plant tissue. Particulate material from the water column, such as dead phytoplankton or zooplankton, also forms detritus. Detritus is classified as “autochthonous,” detritus that originates from within the ecosystem; or “allochthonous,” detritus that is transported into the ecosystem. Because of gravity, detritus usually sinks to the sediment, where it is either decomposed by microbes or becomes buried. Detritus is decomposed by bacteria, fungi, and yeast that convert the detritus into nutrients and energy through a process called “mineralization.” In addition to microbes, other animals, including benthic meiofauna and macrofauna invertebrates, can affect the amount of detritus in the sediment by defecating sediment they consume.

#### **4.3.3.3 Trophic Subsystems**

There are three main trophic subsystems within the bay ecosystem: producers, consumers, and mineralizers (Figure 4-4). Producers can generate biomass and energy from sunlight and atmospheric carbon, and are commonly known as plants, or “autotrophs.” Consumers, including animals and most bacteria, are incapable of generating their own energy or biomass, and must eat producers or other consumers; these organisms are called “heterotrophs.” Consumers also require oxygen for respiration. Mineralizers are a specific kind of consumer. Mineralizers include microscopic bacteria that decompose detritus (organic material) as a food source. They liberate carbon dioxide from the organic matter in the process. The reason they are called mineralizers is because they convert all components of organic matter back to their inorganic forms (i.e., mineral forms).

Life in the bay is dependent upon the sun (Figure 4-4). Producers, such as phytoplankton, require sunlight, carbon dioxide, and nutrients to grow and produce energy. Consumers, such as fish, receive the carbon by eating producers, and the oxygen they need from water. Non-living organic matter is produced from producers and consumers, and “rains down” upon the bottom of the bay. In the sediment, bacteria use oxygen to break down the organic matter to receive energy. Like consumers, these bacteria produce carbon dioxide. Bacteria also release old nutrients back into the water. The three living subsystems in the bay—producers, consumers, and mineralizers—are dependent upon a variety of non-living factors that operate on the bay. For example, new nutrients enter the bay from rivers or as runoff from cities, farms, and other adjacent landscapes. Another factor that affects the bay ecosystem is the ocean. Energy, nutrients, oxygen, and living organisms are all exchanged between the bay and ocean. The rate of exchange is determined by the number and size of passes and by the intensity of the wind and tide. Of all the complex interconnecting sources and components within the bay, man can alter two: freshwater inflow with diversions and return flows, and circulation patterns with jetties and



channels. Altered inflows reduce nutrient flow and sediment transport. The reduced freshwater volumes increase salinity. The effects of freshwater, sediment, and nutrient starvation interact and can create losses of marsh and wetland habitats because of the linkages within the system. Altered inflow can affect other components by changing the salinity ranges within habitats. Many organisms have specific limits to tolerance of salinity range, require low salinity ranges to reproduce, or require the salinity gradient to find nursery habitats.

#### **4.3.4 Estuarine Environmental Indicators**

Ecological integrity can be defined as the condition that exists when measurable physical, chemical, and biological parameters fall within the range of values that historically occurred before man's activities and development modified natural processes. Bay environmental health indicators include water quality, species, and combination metrics that measure various aspects of biological community function and composition. Hypoxia (oxygen deficiency), other eutrophication indicators, concentrations of toxic compounds, and other water quality data routinely monitored by the TCEQ also inform estuary scientists about potential threats to the system. Ecological integrity also means that densities of animals and plants are not significantly different from the historical patterns of abundance. Preserving characteristic biological diversity allows an estuary to remain resilient to natural and man-made disturbances.

Environmental indicators generally include estuarine organisms that respond to changes in salinity conditions caused by changes in freshwater inflow. Responses of many estuarine plants and animals to changes in salinity have been documented. Species-based indicators can include abundance of key species, such as threatened or endangered species, benthic organisms, plant communities or disease organisms. Plant communities serve as good environmental indicators because they are generally rooted in place and their spatial extent is measurable. Distributional shifts in relative abundance of seagrass species are often associated with different environmental factors. For example, water nymph communities are associated with low salinity and high nutrient levels, while widgeongrass and shoalgrass communities are associated with higher salinities and lower nutrient loads. Similarly, for estuarine marsh communities, saltmarsh bulrush is associated with lower salinity conditions than smooth cordgrass.

Oyster reefs can also serve as environmental indicators since oysters spend their entire adult life in the estuary as sessile (fixed) organisms. Approximately 90% of reported commercial Texas oyster landings are from reefs in Galveston, Matagorda, and San Antonio Bays. Oysters are capable of surviving a fairly wide range of salinity conditions, but high salinities are thought to limit oyster abundance in estuaries of the lower Texas coast. Oysters are also subject to predation by other organisms that can survive high salinity conditions, significantly increasing oyster mortality. Adequate freshwater inflows are necessary to keep oyster predators and diseases in check.

## **5. ENVIRONMENTAL FLOWS**

### **5.1 Rivers and Streams**

#### **5.1.1 Role of Environmental Flows**

Environmental flows play an instrumental role in supporting and conserving biological resources in Texas rivers and streams. Environmental flow regimes largely determine the amount and condition of habitat available to aquatic and riparian organisms. Flow regimes that vary over time create a mosaic of diverse habitat conditions that in turn support diverse floral and faunal assemblages. The life cycles of aquatic organisms are often phased with seasonal flow events and include spawning and migration. Flowering, seed dispersal, germination, and growth of riparian plants may also be tied to flow events.

Streamflow influences the physical factors of current velocity, eddy circulations, and transport of materials, including small woody debris. Sediment flushing, sediment transport, and stream channel formation and maintenance occur over a range of moderate to high flows. Natural channels and floodplains can moderate the impacts of flood events. Water quality (e.g., water temperature and levels of oxygen) in rivers and streams is also influenced by varying flows and dictates the survival, growth, and reproduction of aquatic organisms. For example, low flows during hot summer months can lead to elevated water temperatures and low levels of dissolved oxygen, which create inhospitable conditions for fish and wildlife. Rivers and streams and their floodplains assimilate nutrients and organic matter from natural and human sources such as runoff and wastewater. Without adequate flows, decomposition of organic matter can lead to oxygen depletion.

Flow regimes also facilitate connectivity, the movement and exchange of nutrients, sediments, organic matter, and organisms within the riverine ecosystem, its floodplains, subsurface habitats, and receiving estuaries. Lateral connections between the river and the floodplain are important for maintaining hardwood bottomlands, wetlands, and other diverse riparian systems. Longitudinal connections allow migrating species to fulfill critical life history events such as successful spawning and recruitment. Vertical connections between the river and its subsurface environment support diverse assemblages of microorganisms and invertebrates and promote productive riverine environments.

A varied flow regime that mimics natural historical patterns and that maintains adequate sediment loadings is the key to sustaining the fish and wildlife resources within and adjacent to Texas rivers and streams. Those environmental flows must include inter-annual and intra-annual variations at appropriate frequencies to maintain the inherent complexity of habitats and physical-chemical conditions upon which biological communities depend. Flows during drought periods can be especially critical with respect to maintaining biological resources in rivers and streams.

### **5.1.2 Habitat Relationships**

River and stream channels are not only conduits for transporting water, but also sediment. Flowing water transports sand, silt, gravel, and other material from where it was eroded to where it is deposited in the river channel or floodplain. The dynamic equilibrium between erosion and deposition creates the river slope and geometry of the channel, forming the physical foundation of instream habitat—riffles, runs, and pools. Changes to sediment supply also can cause significant changes in habitat. Habitat conditions in rivers and streams are characterized in terms of current velocity, depth, bottom substrate, and cover, particularly large woody debris accumulations. These conditions are flow dependent, meaning that their character changes as flow changes. For example, rivers tend to become deeper and faster as flows increase, and shallower and slower as flows decrease.

Riffles are shallow habitats with water swiftly moving over clean cobble and gravel substrates. Many types of river fishes (darters and minnows) live, feed, and reproduce in riffle habitats. They also typically harbor many forms of narrowly adapted invertebrates, such as stoneflies, hellgrammites, and riffle beetles. Riffles are typically very sensitive to changes in flow since they are dewatered first when flows are reduced or cease. Runs are deeper with more moderate current speeds over a variety of substrates. Suckers, sunfish, and some minnows and darters utilize runs for parts of the life cycle. Pools are typically deeper with very low current speeds and little surface turbulence. Sunfish, some basses, and catfish are often found in pools. Instream cover—large woody debris and undercut banks—is an important feature of many habitats and serves as protection from predators and sources of food for invertebrates and fish. Oxbows, wetlands, and other out-of-channel habitats provide areas for fishes, amphibians, reptiles, and birds to find food, reproduce, and raise young. Some species, many of them found only in Texas, find homes in unique habitats such as springs and spring runs.

## **5.2 Bays and Estuaries**

### **5.2.1 Role of Environmental Flows**

Freshwater inflows basically define estuaries. Estuaries, by definition, are semi-enclosed coastal water bodies where freshwater flowing from rivers and streams meets and mixes with saltwater from the open ocean. Influxes of freshwater also provide essential nutrients and sediments that nourish estuarine ecosystems. The nutrients that accompany inflows in the form of organic detritus act as a food supply for many estuarine organisms. The characteristics of Texas estuaries are determined ultimately by factors that include climate, landform morphometry, their relatively restricted access to the Gulf, freshwater inflow volume and variation, and the kinds of materials delivered into the bays.

Freshwater inflows to Texas bays and estuaries are dynamic in nature, fluctuating seasonally and annually. This variability, within limits, is important and beneficial for estuaries. Seasonal timing of freshwater inflows is critically important for providing proper conditions for reproduction and growth. Floods and droughts occur in nature, and Texas estuaries have adapted accordingly. Floods periodically flush pollutants and control nuisance species populations, while droughts, if not too severe or frequent, can be tolerated by healthy estuarine ecosystems. Thus, the frequency, or periodicity, of these events is equally important. These long-term influences on

the freshwater inflow regime are manifest in the habitats, including surrounding wetlands, which further characterize estuary integrity, productivity, and aesthetic value.

Chronic reduction of freshwater inflows can lead to alterations within an estuary, including increasingly high salinity levels, reduced bay circulation patterns, and diminished nutrient and sediment loads. Over time, these changes can result in a shift in endemic species composition within the estuary, potentially leading to decreased recreational and economical utility of the system. Proper levels of environmental flows, appropriately timed and varied in frequency and duration, can provide the means to maintain historical species composition and abundance when an estuary is faced with reduced freshwater flows as a result of human activities such as upstream water diversions or reservoir construction.

### **5.2.2 Habitat Relationships**

Major habitats in Texas bays and estuaries are wetlands, open bay bottoms, shorelines, reefs, and seagrasses. All of these habitats are important components that support aquatic resources.

Wetlands serve as important nursery and feeding habitats for estuarine organisms, creating low-salinity nursery areas important to juveniles of many finfish and shellfish species found in Texas bays and estuaries and the Gulf of Mexico. Wetland habitats consist of salt marshes, brackish marshes, freshwater marshes, and areas of submerged vascular plants such as seagrasses. Along the Texas coast, marsh types vary from north to south, depending on the amount of freshwater inflow typically received. Wetlands grade in character and species composition along the coastal inflow gradient. Upper coast estuaries such as Sabine Lake, Trinity Bay, and Galveston Bay typically have lower salinity levels and are characterized by brackish and freshwater wetlands with plant communities that are sensitive to increases in salinity. Mid-coast estuaries like Matagorda, San Antonio, Copano, and Aransas Bays are generally characterized by more tolerant saltmarsh ecosystems. Corpus Christi Bay and Laguna Madre on the lower coast are home to succulent halophytes (salt-tolerant plants) that include saltwort, glasswort, and black mangrove.

Open bay bottoms vary according to incoming sediments, nutrient richness, and water depth. Inflow sediment amount and character and tidal velocities influence the proportions of sand, clay, and organic silts, which influence benthic faunal richness. Oyster reefs typically are able to build where salinities are optimal for growth. There may be a salinity gradient with respect to distance from the river mouth and the typical amount of inflow where optimal oyster growth can occur. A gradient from river mouth to bay pass exists for sediment, as well as shoreline wetland habitats, and it is locally important to maintain these unique diversity and productivity areas within each estuary. Likewise, a down-coast gradient due to decreasing freshwater inflow volume in the same down-coast direction is important to maintain historical species diversity and productivity across the entirety of Texas bays and estuaries.

## **5.3 Economic Considerations**

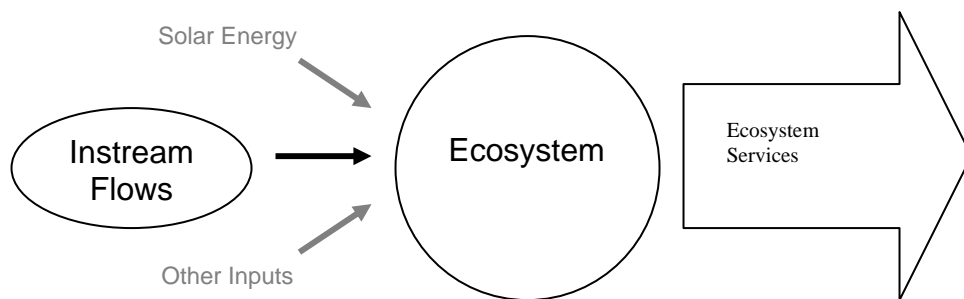
### **5.3.1 Economic Importance/Implications**

One of many uses of instream flows is ecosystem sustainability, a general term that comprises a variety of uses for water that is left in the stream channel (or other water body), rather than

diverted or impounded for use “off-stream.” In addition to ecosystem sustainability, these uses include outdoor recreation activities, navigation, hydroelectric generation, waste assimilation (sometimes termed water quality), conveyance to downstream points of diversion, and the provision of aesthetic beauty (U.S. Water Resources Council 1978).<sup>3</sup> It is important to note that many of these uses occur simultaneously, derived from the same flows that exist at any given point in time and space. Thus, water left instream for environmental purposes may also generate a variety of significant additional benefits associated with these other uses. While recognizing the economic importance of these other benefits, this section of the report focuses on the economic benefits specifically associated with environmental flows.

For the most part, the economic benefits attributable specifically to environmental flows are closely linked with goods and services provided by the ecosystem, or by the water itself as a component of habitat. Examples of ecological services include the provision of species stock available for commercial and recreational harvest, the maintenance of habitat (which provides a variety of beneficial functions such as erosion control, water quality improvement, nursery areas, water storage, and aesthetic beauty), nutrient cycling, biodiversity (which provides resilience and attracts ecotourists), and the control of nuisance species. Some of the goods and services provided by the ecosystem can be captured and sold in markets as private goods. The harvesting of a variety of fish and shellfish species is the most obvious example. Indeed, Texas’ commercial coastal fisheries contribute significantly to the gross state product. However, most ecosystem goods and services do not pass through markets, and are delivered directly to the consumer, at no charge. Such goods and services are referred to collectively as “non-market benefits.” Despite the absence of a price, these benefits are economically valuable.

As the many beneficial functions provided by the ecosystem become better understood, and as the non-market benefits the ecosystem bestowed upon humans become more widely appreciated, significant research attention has begun to focus on the economic value associated with ecosystem services (Costanza et al. 1997; Daily 1997). Although there is often considerable debate about the methods used and the accuracy of the values derived, there is little doubt that the un-priced economic value of ecosystem services is enormous. Because most ecosystems require water to remain healthy, the value they generate through their many beneficial services is partially attributable to the water needed to sustain them (see Figure 5-1).



**FIGURE 5-1 RELATIONSHIP OF INSTREAM FLOWS TO ECONOMICALLY VALUABLE ECOSYSTEM SERVICES**

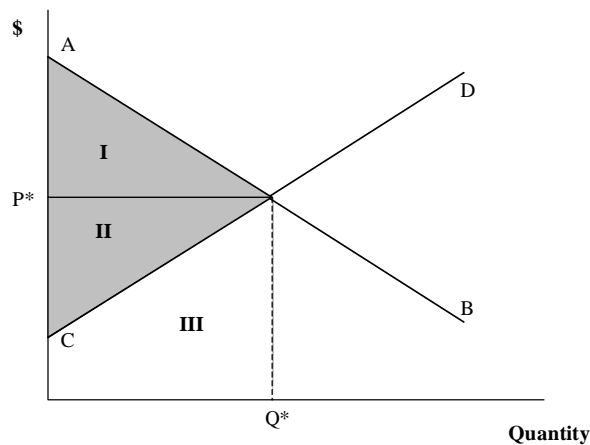
<sup>3</sup> See also Colby (1990, 1989b); MacDonnell et. al, (1989); Gibbons (1986).

Economic consideration regarding the benefits of environmental flows can be viewed as involving two different but often related concepts: the *economic value* generated by environmental flows, and the *economic impacts* associated with changes to the temporal and spatial distribution of environmental flows. Each of these concepts is discussed briefly below.

### 5.3.1.1 Economic Value

Considerable confusion often exists regarding the terms “economic value,” “market value,” and “market price.” These terms refer to quite different concepts, but are, nonetheless, often mistakenly used interchangeably. Thus, before moving forward with the discussion of the economic value of water to sustain the ecosystem, it is useful to discuss what is meant by the term “economic value.” Economic theory contains a number of concepts pertaining to value. Some of the most fundamental of these notions are represented in Figure 5-2, which presents a simple depiction of a “market” in which the consumer and the producer interact to generate an equilibrium price,  $P^*$ , and a quantity,  $Q^*$ . This graph contains a variety of important information regarding economic value, derived from certain characteristics of consumers and producers, and the relationship of these characteristics with the market.

**Marginal Costs and Marginal Willingness to Pay** - First, consider line segment AB, which maps out the consumer’s “marginal willingness to pay” for each successive unit of the goods in question, to form the “demand curve.” Its downward slope reflects “decreasing marginal utility,” i.e., the notion that the value to the consumer of each successive unit of the goods decreases as the individual obtains more units of the goods. This line is also often referred to as the “marginal benefits” curve. Turning now to the producer (the firm), consider line segment CD. This line represents the firm’s “marginal costs,” i.e., the costs associated with producing each successive unit of the good. The marginal cost curve’s upward slope reflects the idea that firms will utilize “low-hanging fruit” first, and as more units of the goods are produced, accessing “fruit higher in the tree” increases the cost of production. The marginal cost curve is also the foundation of the familiar “supply” curve.



**FIGURE 5-2 FRAMEWORK OF ECONOMIC VALUE**

**Market Price** - When the consumer and producer come together with “mutual coincidence of wants” to form a market, the consumer will accept a price no higher than his willingness to pay, and producers will accept a price no lower than their cost of production (willingness to sell). The equilibrium market price  $P^*$  occurs at the number of units  $Q^*$ , where the marginal benefits to the consumer equal the marginal costs to the producer. In other words, price simultaneously matches the consumer’s willingness to pay and the producer’s willingness to sell, thus “clearing the market” i.e., at  $(P^*, Q^*)$  there is no gap between marginal willingness to pay, marginal willingness to sell, and the market price. No trades for additional units of the goods will occur because the price exceeds the consumer’s willingness to pay, and falls below the producer’s marginal cost. It is important to recognize that the market price  $P^*$  reflects *only* the value of the last unit,  $Q^*$ , exchanged in the market, and this value is identical for both the consumer and the producer. Because the market price increases or decreases according to changes in supply and demand—for example, a decrease in supply or increase in demand will both lead to a higher price—price is relied upon as an indicator of economic scarcity, as is sometimes even referred to as “scarcity value.” The scarcer the goods, the higher is the price, and visa versa.

**Economic Surplus** - For each unit exchanged in the market previous to  $Q^*$ , a gap exists between the consumer’s willingness to pay, the producer’s marginal costs of production, and the market price at which those units were exchanged. The difference between the consumer’s marginal-willingness-to-pay curve and the producer’s marginal-cost curve for each successive unit of the goods is referred to as “marginal surplus” (or marginal net benefits). This marginal surplus is divided between the consumer and the producer. For each unit, the consumer surplus is the amount by which his willingness to pay exceeds the market price, while the producer surplus is the amount by which the market price exceeds the marginal cost. Total consumer surplus is found by summing up the marginal consumer surplus for each unit of the goods up to  $Q^*$ , and is represented in Figure 5-2 by shaded triangle I. Similarly, total producer surplus is represented by shaded triangle II. Total surplus is the combination of both consumer and producer surplus, represented by both shaded triangles, and can be viewed as the total net benefits to society achieved by the production and consumption, sale, and purchase, of  $Q^*$  quantity of the goods. In the standard neo-classical economic model presented here, it is total surplus that is typically used as the definition of economic value. Total benefits, i.e. economic value, are maximized at the point where marginal benefits (willingness to pay) are equal to marginal costs, and the market outcome is said to be “efficient” because no further trade can be made that increases these total benefits. The maximization of total benefits is one of the fundamental objectives of the economic decision-making process.

Observe that economic value, defined as total surplus, is *not* the same as market value. Market value is simply the producer’s revenue—the number of units sold,  $Q^*$ , multiplied by the price,  $P^*$ . While market value includes the producer surplus, represented in Figure 5-2 by triangle II, it also includes the cost of producing  $Q^*$ , represented by area III. Moreover, it does not include any surplus that accrued to the consumer (triangle I).

### 5.3.1.2 Economic Impact

A second concept relevant to economic consideration of environmental flows is “environmental impact.” Economic impact is a broad concept often used to understand the pros and cons of changes associated with implementing a project or policy, in terms of the economic system that is affected. Analysis of economic impact can include changes in economic value, as described

above, but economic impact is *not* the same as economic value. It typically includes estimates of “direct” effects (e.g. changes in direct revenues and income, changes in the number of jobs) and may also include estimates of secondary effects that result as direct effects work their way through the economic system. For example, a policy or project that yields direct negative impacts on the local fishing industry may also yield negative secondary impacts on the coastal community that provides the fishing industry with a variety of goods and services. When considering increases or decreases in income/revenue, a “multiplier” is often used to capture some of these secondary effects.

Thorough efforts to analyze economic impact should also include estimates of changes in “intangible” non-market economic values, in terms of losses or gains associated with resulting ecological impacts and changes in ecological benefits. Economists widely recognize that the omission of non-market economic values can result in assessments of economic impacts that are highly skewed and inaccurate.

In general, the economic impacts of a change in the allocation of water will make some people better off and others worse off, and these losses and gains are not distributed equally across neighborhoods, cities, counties, regions, and states. It is therefore important to examine *where* the economic impacts of a project or policy occur. Although economic theory can contribute extensive insights regarding efficiency and the objective of maximizing total benefits, it provides relatively little guidance as to whether one distribution of losses and gains is better than another.

### **5.3.2 Economic Value of Instream Flows**

It is widely recognized that the price actually paid to use water, if one is paid at all, rarely reflects its full economic value. For many uses the price of water is merely determined by the cost (often heavily subsidized) of providing it, rather than the interaction of many buyers and sellers (i.e., supply and demand) in a competitive market. For many other uses, no price exists at all. Such is the case with environmental flows (and instream flows in general). Thus, in the vast majority of cases, prices provide very little information about the water’s true economic value.<sup>4</sup> After decades of intensive research, the value of water used in many agricultural, industrial, and municipal contexts is relatively well understood. Yet for many other uses of water, including uses of instream flows, estimating the economic value is more difficult and remains poorly understood.

The value of environmental flows arises from two basic sources: (1) the value water as an “intermediate input” to the ecosystem’s production of beneficial goods and services; and (2) direct “non-use” values that involve the willingness to pay to maintain the habitat or ecosystem, without actually physically enjoying any of its attributes. In addition, as noted above, water left to sustain the ecosystem may also be used for a variety of other purposes that yield significant additional economic value. Each of these will be discussed in turn.

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<sup>4</sup> The result can be tremendous inefficiency with regard to the use of water. This inefficiency is exacerbated if no price exists at all. In theory, this inefficiency can be remedied if the price of water accounts for all private and social values associated with water’s various uses. In this situation, the market price would motivate choices that lead to the optimal use of water, in which water is allocated and used in a way that yield the most benefits to society.



### 5.3.2.1 Indirect Value from Ecosystem Services

Recalling Figure 5-1 and the associated discussion, environmental flows are an important “input” to the ecological production process that yields a variety of ecosystem services. Consequently, a relationship exists between water used to sustain the ecosystem and the benefits the ecosystem provides. Whether the ecosystem services are captured and sold in the market (e.g. fish) or whether they benefit the consumer directly without passing through a market, a portion of the economic value that they generate is attributable to environmental flows. Researchers are just beginning to study the economic relationship between environmental flows and ecosystem services, so few estimates of economic value derived from this relationship exist.<sup>5</sup> Nonetheless, given the enormous value associated with ecosystem services, it is likely that in many cases the portion of this value attributable to water is also quite large.

### 5.3.2.2 Direct Non-Market Value

The absence of prices for instream water has led to significant efforts to estimate the value of water for instream uses using non-market valuation approaches. Most of these studies consider recreational uses, such as fishing or rafting, while only a very few seek to estimate the value of instream flows in sustaining the ecosystem (i.e., environmental flows). Because there is no “producer” of instream flows, neither is there a marginal cost curve or a price. Consequently, the economic value of the non-market goods and services it provides is based on the benefits that accrue to the users of these goods and services.

Direct values from environmental flows generally arise from a type of economic value known as “non-use” value. Non-use values of environmental flows reflect individuals’ “willingness to pay” for this water, even though they do not expect to use it or benefit from it (at least immediately). Such values are also sometime referred to as “preservation” values. Non-use values generally arise from three sources: (1) the desire to preserve the option of the individual to enjoy the benefits of instream flows—e.g., recreation, experiencing a healthy ecosystem—at some point in the future (option value); (2) the desire to leave this option as a legacy for others in the current generation and/or those in future generations to enjoy (bequest value); and (3) the satisfaction derived simply from knowing that water flows will ensure that an ecosystem or habitat will continue to exist (existence value).

Perhaps due to the methodological complexity of estimating non-use values for instream water, and for environmental flows in particular, few such studies have been undertaken. However, the scant existing literature suggests that non-use values can be large, especially for unique recreation sites or for the preservation of endangered species and unique ecosystems (Walsh et al. 1984). In Wyoming, Colorado, and Alaska, non-use values have been estimated at \$40 to \$80 per non-use household per year (Greenley et al. 1982; and Madariago and McConnell 1987). Another study finds evidence that non-use values of instream water are substantially greater than use values (Schulze et al. 1983). A study of California’s Mono Lake estimates that non-use values accounted for more than 80% of the total willingness to pay to preserve the lake’s level (Loomis 1987). Finally, Berrens et al. (2000) investigated the value of non-market benefits of protecting minimum instream flows in four New Mexico Rivers: the Gila, Pecos, San Juan, and

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<sup>5</sup> Mathis (2004) has explored the value of environmental flows as a critical intermediate input to the production of ecotourism.

the Middle Rio Grande.<sup>6</sup> The willingness to pay to protect minimum instream flows in all four New Mexico rivers together was \$73.99 per year, while mean willingness to pay to protect minimum instream flows in the Middle Rio Grande alone was \$57.04 per year.<sup>7</sup> Few (if any) such studies have examined instream flows in Texas.

While recognizing the existence of non-use economic values for instream flows, valuation research has focused on “use” values, primarily those associated with recreational activities such as fishing and rafting. As mentioned above, these values are not the same as the value of environmental flows, but can be complementary to it when environmental flows are also used for recreational objectives. A recent study of the recreation benefits of instream flow in Montana’s Big Hole and Bitterroot Rivers, for example, estimates marginal recreational value ranging from \$10 to \$25 per acre-foot per year at 100 cfs, decreasing to \$0 as streamflow increased to 2,000 cfs (Duffield et al. 1992). Daubert and Young (1981) estimate annual marginal instream benefits from recreation during low flows on Colorado’s Cache la Poudre River at \$17 per million cubic meters (Mm<sup>3</sup>) for fishing and \$12 per Mm<sup>3</sup> for shoreline recreation (also falling to zero as streamflow increased). Another study of Colorado rivers finds that optimal streamflow for recreation is on the order of 35% of the maximum, and estimates the annual value of an additional Mm<sup>3</sup> beyond the 35% streamflow at \$17 for fishing, \$4 for kayaking, and \$3 for rafting (Walsh et al. 1980; cited in Colby 1990a). Research on instream recreation in northern Utah finds that the annual marginal value of water is zero until streamflow drops below 50%, and increases to a maximum of \$65 per Mm<sup>3</sup> when flow is diminished to 20-25% (Amirfathi et al. 1984; cited in Colby 1990a)<sup>8</sup>.

### 5.3.2.3 Allocation of Water

Understanding the economic value of environmental flows is important in at least two fundamental aspects of decision making:

1. how to allocate water in a way that generates the most total benefits (“optimal” allocation), and
2. how to account for changes in economic value due to the changes in water allocation associated with implementing a particular project or policy.

It is important to recognize that water is unique among natural resources in the wide variety of uses in which it can be employed. These uses are typically divided into two broad categories: human use, representing municipal, industrial, and agricultural uses; and environmental use, often referred to as environmental flows. This categorization becomes more complex when instream human uses such navigation, hydropower generation, and recreation are also included. Complexities of categorization notwithstanding, the optimal use of the water, as defined by economics, is achieved by allocating it across its various uses in a way that maximizes the total

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<sup>6</sup> “Middle Rio Grande” is a confusing term that has been used to refer to widely differing stretches of the Rio Grande. In this case, it refers to a stretch that lies entirely within New Mexico.

<sup>7</sup> The values of median willingness to pay were between \$20-30 and \$40-50, respectively.

<sup>8</sup> Because estimates of marginal values for ecosystem sustenance are difficult to derive, the value of instream flows for recreational uses can provide a lower bound for the *total* marginal benefits generated by maintaining instream flows (Colby, 1990a).

benefits. Thus, the economic value associated with each use is important to achieving the objective of optimal water allocation based on economic principles.

It is important to distinguish between “water demand” and “water use.” Confusion arises because the term water demand is often used, when water use is what is actually being described. Water use is simply the quantity of water (measured or estimated) used over a given period of time. Future water use is typically calculated by multiplying the population by a per capita water use rate, or in the case of agriculture by multiplying irrigated acreage by a water use rate associated with the appropriate crop. Water use rates used in such calculations can be based on historic or current use rates, as well as various scenarios of future use (.e.g. conservation techniques and technologies).

In contrast, water demand does not assume the existence of a per capita rate, but rather relates quantity of water used to its value to the user, thus incorporating the influence of scarcity, price, and economic value in water use decisions. Perhaps more importantly, water demand can reflect the fact that human water demands for agricultural, municipal, and industrial purpose are actually aggregations of multiple uses exhibiting different economic value. For example, municipal water demand is composed of the demand for water for a variety of purpose, ranging from drinking, bathing, and laundry (high value), to irrigating lawns, washing cars, and filling swimming pools (low value). Similarly, agricultural demand is composed of water used to irrigate crops, ranging from alfalfa and sugar cane (low value) to herbs, fruits, and vegetables (higher value). Thus, total human demand for water is an aggregation of water for a variety of purposes, ranging from very high to very low value.

This distinction between water demand and water use becomes particularly important when discussing trade-offs between environmental flows and human uses of water. The notion of water demand allows evaluation of environmental flow allocation in the context of the wide spectrum of low to high value uses of water. While it is certain that environmental flows would *not* be ranked above high value uses (e.g. drinking) in terms of trade-offs, it is also quite possible that they *would* be ranked above many low value uses (e.g. irrigation of lawns and alfalfa).

Because water often exists as streamflow—rather than an impoundment—spatial and temporal considerations may also be important in pursuing optimal water allocation. Seasonal differences may be important in shaping the optimal allocation pattern over the course of a year, while regional differences may be important in shaping the optimal allocation pattern over a geographic area. Finally, the spatial aspect of water flows gives rise to upstream-downstream dynamics that may also play a role in shaping optimal allocation.

While optimal allocation of water is a key objective of economic decision making, it is by no means the only criteria that can be used to determine the allocation of water. In fact, rarely is water allocated based on the criteria of economic efficiency. Political, social, and environmental/ecological criteria are also important considerations. As described elsewhere in this report, the allocation of water in Texas is based on a complex system of water law and regulation. Water is allocated, in the form of water permits, on a first-in-time, first-in-right basis (prior appropriation doctrine).

In the case of instream flows, ecological criteria (i.e. the instream flow needs of the ecosystem) could play a primary, if not determining, role in determining the allocation of water to sustain the

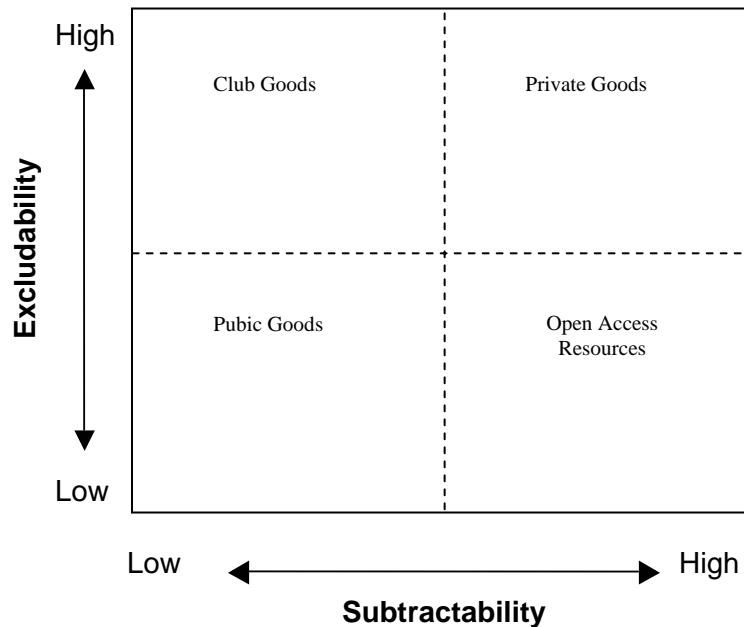
ecosystem. However, once instream flows are allocated based on ecological criteria, economic considerations could yield insights regarding achieving these ecologically determined instream flows in the least-cost fashion. In addition, because these same flows provide benefits to humans via recreation, aesthetics, hydro-power generation, etc., as noted above, economic analysis can help quantify the value these additional benefits.

The economic value of water may also be important in the assessment of the costs and benefits of implementing a particular project or policy that will result in a change from the *ex ante* allocation of water. This is especially germane to the impacts on ecological services caused by changes in environmental flows.

#### **5.3.2.4 Public Good**

It is important to note that environmental flows are “public” use of water, in which the same water is (or can be) shared by multiple users, often for multiple purposes. In contrast, off-stream uses for agriculture, industry, and municipal purposes are primarily “private” uses in which water used by one consumer is not available for another. Indeed, instream flows in general, and environmental flows in particular, exhibit unique characteristics that have important implications in the determination of economic value. Because of these characteristics—low subtractability and low excludability—economists typically categorize instream flows, including environmental flows, as a “public good.” Public goods, as defined by economists, exhibit: (1) a very low degree of “subtractability” (the use of the good by one person does not reduce the amount of the good available to another); and (2) a very low degree of “excludability” (once the public good is provided, it is difficult or impossible to exclude others from the benefits that the public good generates, see Figure 5-3). Often-cited examples of public goods (or services) include national defense, lighthouses, and fireworks displays. Environmental protection and ecosystem preservation is also a public good, within which falls environmental flows. In contrast, private goods—by far the category of goods with which we are most familiar (e.g., food, clothing, housing, computers)—are at the opposite end of the spectrum, in that they are both highly subtractable and highly excludable. Assuming rule of law prevails, the purchaser of a pint of ice cream, for example, is recognized as the owner, who can legitimately exclude others from appropriating and consuming the ice cream. The pint of ice cream is also perfectly subtractable, in that once the consumer eats it, there is one less pint available for him or anyone else to consume thereafter.

Public goods also differ from private goods in terms of “divisibility of benefits.” In the standard case of a private good, consumers have little control over the price, which is “determined by the market”; they respond to the price by adjusting the quantity of the good to purchase, so that the willingness to pay (benefits) for the last unit of the goods equals the price. In contrast, the benefits of public goods are highly indivisible; once the public good is provided, consumers cannot choose how much to consume. In the case of environmental flows, once they exist, we all have little choice but to “consume” that level (quantity) of environmental protection. However, the value we each attach to that level of environmental protection may vary considerably. Thus, with private goods, the value (price) remains the same for all consumers, but the value varies. This may appear to be a somewhat technical distinction, yet it yields entirely different methods for determining the total economic value to society of the “consumption” of the good.



**FIGURE 5-3 TYPOLOGY OF ECONOMIC GOODS BASED ON EXCLUDABILITY AND SUBTRACTABILITY**

The public-good aspects of environmental flows also present an additional layer of complexity when considering allocation of water, and the mechanisms by which that allocation might be achieved (Colby 1989a).<sup>9</sup> Recognizing the unique public good characteristics of environmental flows is fundamentally important to the economic consideration of this water use.

While rather technical, this discussion serves to emphasize that the unique public good characteristics of environmental flows are fundamentally important to the economic consideration of water used to sustain the ecosystem. In a number of dimensions, environmental flows cannot be approached in the same way that traditional private goods are approached.

<sup>9</sup> In particular, the public-good character of instream flows poses challenges to market-based allocation approaches. It is well established that when the provision of a public good is left to market decisions, the good may be under-supplied due to the free-rider problem. An additional complication follows from the non-subtractable aspect of instream flow; once this flow has been provided, the optimal charge to additional users is zero, a situation for which the market may not be well suited.

## **6. AVAILABLE ENVIRONMENTAL FLOW ASSESSMENT TOOLS**

### **6.1 Rivers and Streams**

#### **6.1.1 State Analytical Methodologies**

There are two distinct types of methods that are used by the state agencies for estimating environmental flow needs for instream uses in rivers and streams: statistical “desk-top” techniques, sometimes referred to as “standard-setting” methods; and “comprehensive” methods involving intensive field studies and integrated biologic/physiographic/hydraulic analyses, which are sometimes referred to as “incremental” methods.

The statistical desk-top techniques typically involve statistical analyses of existing daily streamflow records for a potential water development site and the selection of specific flow values with particular frequencies of occurrence that are intended to represent minimum streamflows required for environmental protection under certain conditions. These desk-top methods (i.e., rule-of-thumb methods) are used to develop flow targets, limits, or minimums below which water can no longer be diverted or stored for human use. Desk-top methods typically are used where field studies have not been carried out. This is typically in low risk, less complex, and low-controversy situations, routine evaluations of water rights permits, and/or in preliminary or planning-level assessments. These methods are generally inexpensive, relatively fast to apply, and do not require data collection or a high level of technical expertise. Since these methods typically do not validate linkages between aquatic ecosystem integrity and hydrology, they are not considered to be scientifically rigorous.

The comprehensive methods involve site-specific data collection and hydraulic modeling to support the assessment of the actual flow regime needed for existing habitat maintenance along a particular stream segment. These methods are generally considered to be more defensible than the statistical desk-top, standard-setting methods. Comprehensive methods are typically used in project-specific assessments with high levels of controversy or of risk relative to fish and wildlife impacts. They also tend to have many decision variables. The effort, expense, and expertise required is much greater than with desk-top methods; in general, all involve collecting or obtaining more extensive data than desk-top methods. Most comprehensive methods utilize instream habitat modeling (i.e., predicting how river habitat changes with flow), but may also address water quality, physical processes, riparian areas, and other riverine processes and functions. They can be used in decision making through alternatives analysis and quantification of relationships between streamflow and specific ecological objectives (e.g., amount of spawning habitat). These more comprehensive studies often are required as part of state and federal permitting.

Following are descriptions of the two specific statistical desk-top methods used by the state for estimating environmental flows for rivers and streams and a brief discussion of the most widely used comprehensive method involving field studies and modeling that has been employed for evaluating the instream flow requirements for specific water development projects. The application of the basic concepts of this more comprehensive method also is described in Section

6.1.2 as part of the discussion of the state agencies' proposed program for developing environmental flow needs for rivers and streams pursuant to the requirements of Senate Bill 2.

#### **6.1.1.1 Consensus Planning Criteria Method**

State and regional water planning in Texas requires the use of the Consensus Planning Criteria (CPC) method to assess and establish the environmental flow requirements for all new water supply development strategies, when site-specific field studies are not available or feasible during regional planning efforts ([www.twdb.state.tx.us/RWPG/twdb-docs/env-criteria.htm](http://www.twdb.state.tx.us/RWPG/twdb-docs/env-criteria.htm)). Flow values derived using the CPC statistical desk-top method are intended to protect the long-term health of the aquatic environment. The general concept of the CPC method was developed through extensive collaboration among scientists and engineers from the state's natural resource agencies (TWDB, TPWD, and TCEQ), as well as academic representatives, consultants, and informed citizens. The actual numerical criteria incorporated into the method for establishing environmental flow conditions are based primarily on intuition regarding environmental flow needs, rather than site-specific field data and scientific principles, and while this method has been used for determining environmental flow needs for planning purposes, it has not been utilized to any significant degree for establishing the specific environmental streamflow restrictions incorporated in new water rights permits or permit amendments.

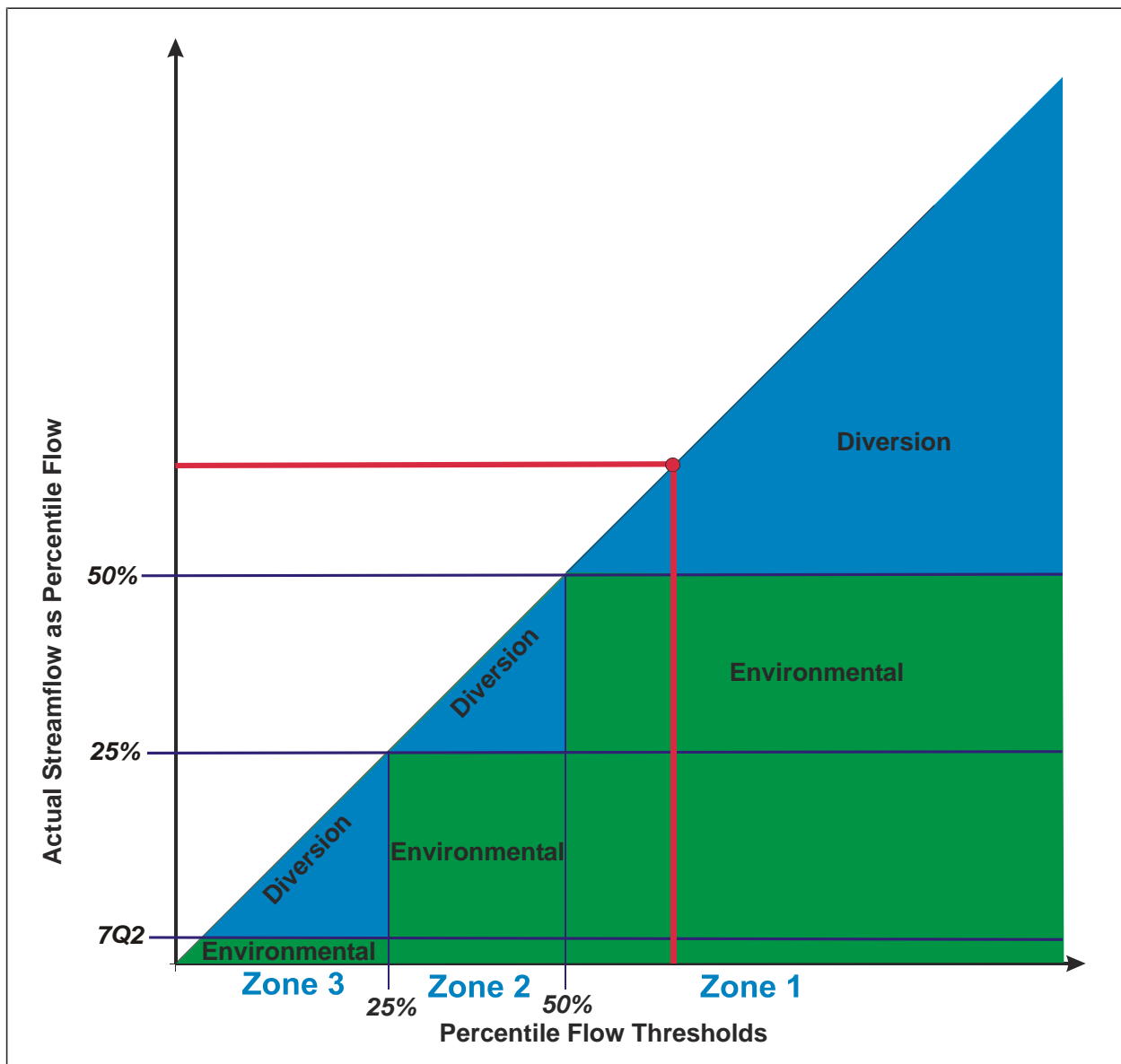
The CPC method is composed of multistage rules for passing streamflows by diversion points and through reservoirs to provide minimum flows for protecting downstream environmental uses. Three levels of hydrologic conditions are considered: Zone 1, above-normal; Zone 2, below-normal; and Zone 3, drought. For direct diversions on streams (with no reservoir), the default criteria for establishing the thresholds between these three hydrologic zones are the median flow (flow that is exceeded 50% of the time) and the 25-percentile flow (flow that is exceeded 75% of the time). For reservoirs, the 50-percent and 80-percent storage capacities are used to define the zones.

The hydrologic condition (zone) of a stream or reservoir determines how much flow must be passed downstream for environmental purposes. The default values of the minimum flows that are required to be passed downstream are: for Zone 1, the median flow; for Zone 2, the 25-percentile flow; and for Zone 3, the greater of the flow required either to maintain downstream water quality<sup>8</sup> or to ensure that a continuous flow will be sustained downstream. As originally formulated, the recommended procedure for applying the CPC method is to use naturalized historical flows, as opposed to actual measured historical flows, for establishing the required median and 25-percentile flow values. The choice of flow data base can make a considerable difference with regard to environmental flow values and is subject to considerable debate among users of the method. One argument suggests that the use of naturalized flows provides higher environmental flow targets that can help restore biological conditions (enhancement). Another position is that the use of historical flows better represents the actual conditions to which existing stream biota have adapted (maintenance).

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<sup>8</sup> Under TCEQ rules, the seven-day average low flow with a two-year recurrence interval (7Q2) is considered to be the minimum flow for which water quality standards apply. Hence, this is the flow considered necessary to maintain downstream water quality for purposes of applying the CPC method.

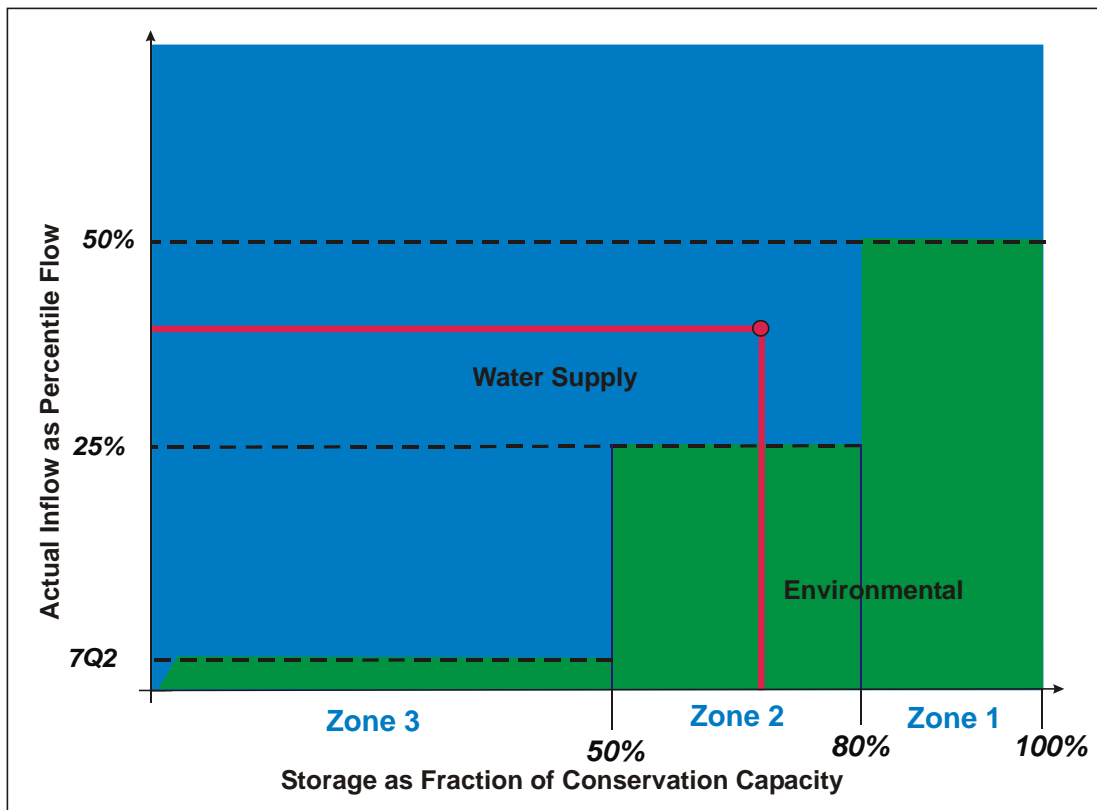
Figure 6-1 illustrates the application of the CPC method to a stream situation (direct diversion) and shows the portion of the streamflows that are available for diversion and the portion of the streamflows that are required to be passed downstream for environmental purposes. The x-axis identifies the flow thresholds (median and 25-percentile flows) that define the three hydrologic zones. The y-axis is the actual streamflow that occurs in the stream, upon which a water user decides how much can be diverted. The green shaded areas represent the flows that are reserved for the environment; the blue shaded areas are the flows available for diversion. For a given flow in the stream, this flow value is entered on the y-axis and followed over to the slanting 45° line, as indicated by the red horizontal line in the figure. At this point (the red dot), the red line is dropped vertically to the x-axis. The part of the vertical red line (flow) that lies in the green-shaded area would be reserved for the environment; the part in the blue area would be available to be diverted for human use.



**FIGURE 6-1 CPC APPLICATION TO FLOWING STREAM CASE**



A similar graph for a reservoir is shown in Figure 6-2. In this case, the x-axis identifies the storage thresholds (50 and 80 percent storage levels) that define the three hydrologic zones. The y-axis represents the actual total inflow that enters the reservoir. The three minimum flows that have to be passed downstream, depending on the hydrologic condition (zone) of the reservoir, are represented by the three horizontal dashed black lines (median, 25-percentile, and 7Q2 flows). For a given inflow amount, this inflow value is entered on the y-axis and projected horizontally to the current value of reservoir storage, as indicated by the red horizontal line and the terminating red dot in the figure. At this point (the red dot), the red line is dropped vertically down to the x-axis. The part of the vertical red line (reservoir inflow) that lies in the green shaded area would be reserved for the environment and passed downstream; the part of the vertical red line between the green shaded area and the red dot would be available to be stored in the reservoir for subsequent human use. It should be noted that in situations where the inflow to a reservoir is less than the downstream environmental flow requirement, only the inflow to the reservoir is passed downstream, and no water is released from storage to satisfy the downstream environmental flow requirement.



**FIGURE 6-2 CPC APPLICATION TO RESERVOIR CASE**

To date, no scientific studies have been completed that verify or validate the appropriateness of the thresholds for delineating the three hydrologic zones used by the CPC method for streams or for reservoirs. Similarly, the magnitudes of the three levels of bypass flows have not been subjected to any type of rigorous scientific analysis. These quantities apparently were simply selected by the state agencies as being appropriate for determining environmental flows.

In the last round of state water planning, culminating in the 2002 State Water Plan, the Regional Water Planning Groups (RPGs) were required to consider the environmental impacts of water management strategies, with the goal of providing adequate water to maintain instream flows and freshwater inflows to bays and estuaries. Some of the RPGs conducted comprehensive analyses of environmental impacts and environmental flow needs, whereas others conducted more limited evaluations. The more comprehensive analyses addressed overall ecological impacts on habitats, fish and wildlife, water quality, instream flows, freshwater inflows to bays and estuaries, and cultural resources and applied the CPC method to establish environmental flow requirements.

### 6.1.1.2 Lyons Method

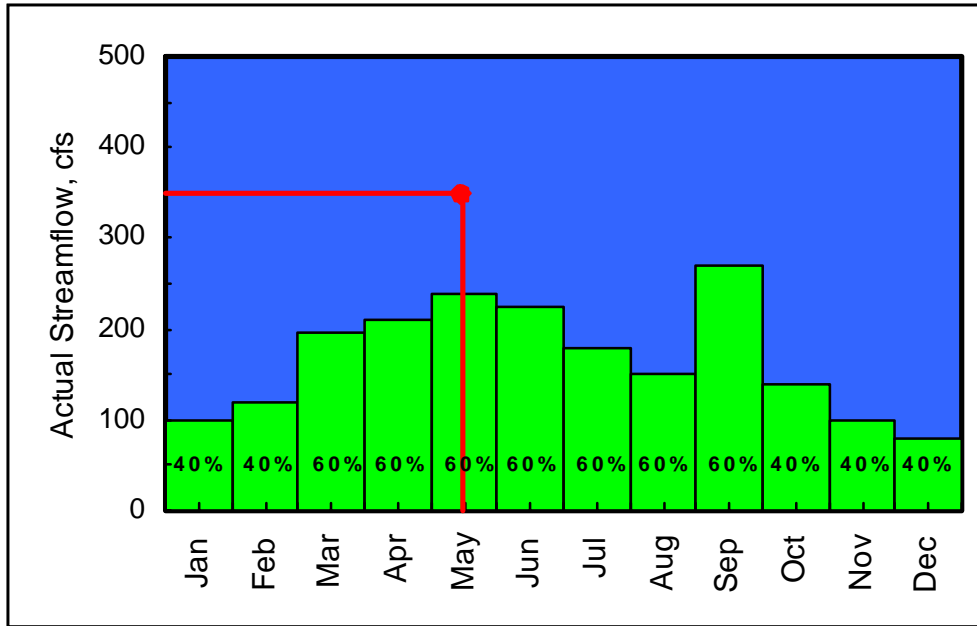
Where extensive field studies are not available and cannot be performed in an expeditious manner to support the establishment of environmental flows for a new permit or permit amendment, the TCEQ relies on statistical desk-top approaches for assessing and establishing environmental flow needs. Typically, the TCEQ applies the Lyons method (Bounds and Lyons 1979) for this purpose. TCEQ sometimes replaces consecutive monthly values with a single corresponding value for each of the months.

The Lyons method was developed by the TPWD. Based on a review of existing literature dealing with assessing instream flow needs—most of which dealt with instream flow methodologies for mountainous western states—the study by Bounds and Lyons combined flow percentages used by Tennant (1976) and median flows recommended by Robinson (1969) as the basis for establishing minimum environmental streamflow levels for each month of the year. The Lyons method utilizes 40% of the historical median daily-averaged flows by month for October through February and 60% of the historical median daily-averaged flows by month for the summer months of March through September as the appropriate levels of streamflow for protecting aquatic resources<sup>9</sup>. The choice of which historical period to use for deriving the historical median monthly flow values is left up to the user, but normally at least 30 years of record are selected to provide a normal range of hydrologic conditions representative of those that existing ecosystems are most accustomed to and to which they have adapted.

Figure 6-3 presents a graphic representation of the monthly environmental flows that result from application of the Lyons method. The y-axis represents the actual streamflow on a stream where environmental flows are required (expressed in terms of cubic feet per second). For any month, the green-shaded area represents the streamflow (on the x-axis) that has to be passed downstream for environmental purposes as calculated with the Lyons method (40% of the median daily-averaged flows by month for October through February and 60% of the median daily-averaged flows by month for March through September). For a given flow amount in the stream during a particular month, this flow value is entered on the y-axis and followed horizontally over to the corresponding monthly green bar, as indicated by the red horizontal line in the figure (to May, in this example). At this point (the red dot), the red line is dropped vertically down to the x-axis. The part of the vertical red line (flow) that lies in the green-shaded area would be reserved for the environment and allowed to pass downstream; the part in the blue-shaded area would be available to be diverted or stored for human use.

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<sup>9</sup> In practice, if the flow determined by the TCEQ with the Lyons method for any given month is below the 7Q2 value for a particular stream, then, in order to protect water quality, the 7Q2 flow value becomes the recommended environmental flow for that month.



**FIGURE 6-3 APPLICATION OF LYONS METHOD**

As part of the original Bounds and Lyons study, field evaluations on the Guadalupe River below Canyon Reservoir were conducted to validate the adopted flow percentiles. These results were reported to support the hypothesis that “40% of the median monthly flow would be needed to maintain aquatic habitat for Texas stream fisheries” and that “to insure suitable spawning habitat and to offset large areas of slack water, which could become stagnant during warmer months, flows greater than 60% would be required during the months of March-September.” There are no known investigations beyond those originally conducted by Bounds and Lyons in 1979 that have validated the applicability of the Lyons method for other Texas rivers and streams; hence, its scientific basis for application to Texas systems is quite limited.

### 6.1.1.3 Instream Flow Incremental Methodology

The Instream Flow Incremental Methodology (IFIM) has been applied for several major water supply and development projects in Texas to establish flow requirements for protecting aquatic resources. This includes studies for O. H. Ivie Reservoir, Little Cypress Creek Reservoir, Lake Bosque, Paluxy Reservoir, Canyon Reservoir (hydropower), and several sites on the lower Colorado River.

The IFIM is the comprehensive methodology most commonly employed within the United States and globally, with applications in at least 20 countries. This methodology, developed in the mid-1970s in the United States (Bovee 1982), uses a set of analytical and modeling tools to address habitat, water quality, sediment transport, and hydrology. Within the IFIM, physical habitat types are described using transects set across stream channels, and corresponding measurements are made of velocity, depth, substrate, and vegetative cover. Data are entered into a spatially one- or two-dimensional hydraulic model to simulate depth-flow relationships, and with data describing how habitat is used by fish and other organisms (i.e., habitat suitability criteria), estimates of how much suitable and unsuitable habitat is available at different flow levels are predicted.

Since the development of this method, advances in habitat modeling have been made. Today, multidisciplinary teams of scientists and engineers continue to refine and improve data collection using: remote sensing, echosounders, and GPS systems; hydraulic engineering using multi-dimensional hydrodynamic models; linkages between biology and streamflow using fish guilds, invertebrates, and bio-energetic models; and spatial analysis using GIS systems. Many of the IFIM concepts are incorporated into the state's proposed Instream Flow Studies Program.

#### 6.1.1.4 Comparison of Environmental Flow Results

Only limited information is available to make direct comparisons of results from the different methods described above for determining environmental flows. The most complete set of results are those developed for the reach of the Guadalupe River downstream of Canyon Reservoir. These results are summarized in Table 6-1 and include environmental flow estimates based on the CPC method, the Lyons method, and the IFIM. It is interesting to note the differences in magnitude between the various flow values. Because of its more comprehensive and scientifically-based approach, the IFIM produces recommended flows that are often considered to be more representative of the actual environmental flows required to protect the existing biological resources in rivers and streams. It is interesting to note, however, for this reach of the Guadalupe River, there really is not a significant difference between the IFIM flows and those derived with the Lyons statistical desk-top method. The CPC Zone 2 and Zone 3 flows also agree fairly well with the IFIM flows; however, the CPC Zone 1 flows are considerably higher. If the IFIM flows actually represent the minimum levels of flow required to protect the biological resources, the need for providing the higher CPC Zone 1 flows half of the time (since Zone 1 is in effect when streamflows exceed the median flow value) may be questionable.

**TABLE 6-1 GUADALUPE RIVER ENVIRONMENTAL FLOWS DERIVED BY DIFFERENT METHODS**

Month	Median Flow (cfs)	IFIM Flow (cfs)	CPC Zone 1 Flow (cfs)	CPC Zone 2 Flow (cfs)	CPC Zone 3 Flow* (cfs)	Lyons Flow (cfs)	Lyons & 7Q2 Flow (cfs)
JAN	164	100	163	91	88	66	88
FEB	178	120	173	100	88	71	88
MAR	183	120	192	95	88	110	110
APR	202	120	188	102	88	121	121
MAY	233	120	244	93	88	140	140
JUN	209	100	186	88	88	125	125
JUL	148	100	116	88	88	89	89
AUG	83	100	90	88	88	50	88
SEP	90	100	117	88	88	54	88
OCT	95	100	150	88	88	38	88
NOV	100	100	151	88	88	40	88
DEC	129	100	171	88	88	51	88

\* Zone 3 flows are 7Q2 values.

Another comparison of the environmental flows derived by different methods is provided with results from the TCEQ’s analysis of the Allens Creek Reservoir project on the lower Brazos River upstream of the city of Richmond. In this case, diversions from the Brazos River are to be made into an off-channel reservoir to be constructed on Allens Creek, a tributary of the Brazos. As the permit is presently structured, the river diversions are to be limited by environmental flow restrictions based on the CPC method applied to Brazos River flows. However, in the process of developing these flow restrictions, the TCEQ also examined flow restrictions based on the Lyons method using both historical and naturalized monthly streamflows. The results from these two analyses are presented in Table 6-2. Again, the Lyons values based on historical flows and the CPC Zone 2 and Zone 3 flows compare favorably, but the naturalized-flow Lyons values and the CPC Zone 1 flows are substantially higher.

**TABLE 6-2 BRAZOS RIVER ENVIRONMENTAL FLOWS DERIVED BY DIFFERENT METHODS**

Month	Historical Median Flow (cfs)	Historical Lyons Flow (cfs)	Naturalized Median Flow (cfs)	Naturalized Lyons Flow (cfs)	CPC Zone 1 Flow (cfs)	CPC Zone 2 Flow (cfs)	CPC Zone 3 Flow* (cfs)
JAN	3,105	1,242	2,566	1,026	2,566	964	734
FEB	4,270	1,708	4,315	1,726	4,315	1,773	734
MAR	3,845	2,307	2,161	1,297	2,161	1,343	734
APR	3,825	2,295	4,601	2,761	4,601	1,835	734
MAY	7,935	4,761	9,059	5,436	9,059	3,159	734
JUN	5,750	3,450	5,575	3,345	5,575	2,596	734
JUL	2,345	1,407	2,512	1,507	2,512	1,139	734
AUG	2,035	1,221	1,379	828	1,379	709*	734
SEP	1,600	960	2,293	1,376	2,293	1,104	734
OCT	1,130	678*	1,483	890	1,483	1,098	734
NOV	2,020	808	2,436	975	2,436	1,100	734
DEC	2,810	1,124	3,048	1,219	3,048	1,055	734

\* 7Q2 values.

### 6.1.2 Texas Instream Flow Studies Program

In 2001, the 77th Session of the Texas Legislature passed Senate Bill 2, which, in part, amended §16.059 of the Texas Water Code to include the collection of instream flow data and the conduct of studies to support the determination of environmental flow needs for rivers and streams in Texas. The legislation directed the TPWD, TCEQ, and TWDB, in cooperation with other appropriate governmental agencies, to “...jointly establish and continuously maintain an instream flow data collection and evaluation program...” In addition, the agencies were directed to “...conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state’s rivers and streams necessary to support a sound ecological environment.”

To facilitate coordination, the agencies developed and executed a Memorandum of Agreement (MOA) in October 2002.<sup>10</sup> The MOA calls for the creation of a coordinating committee and outlines the duties and responsibilities of the three agencies pursuant to implementing the Texas Instream Flow (TIF) Studies program.

For the purposes of implementing the comprehensive instream flow program, Senate Bill 2 dictated that the three agencies establish a work plan that identifies priority studies to be completed no later than December 31, 2010 and sets out a time frame for completion of these studies with interim deadlines. The “Texas Instream Flow Studies: Programmatic Work Plan” was finalized by the agencies in December 2002<sup>11</sup>. In order to complete the priority studies in a consistent and efficient manner, the three agencies also developed the “Texas Instream Flow Studies: Technical Overview” document, which describes in detail how each of the components of the studies is to be carried out.<sup>12</sup> A draft version of this Technical Overview document was produced and circulated for review in August 2003.

The priority studies identified in the Programmatic Work Plan by the three agencies are to be completed not later than December 31, 2010. These studies were identified based on potential water development projects, water rights permitting issues, and related factors. Priority subbasins and associated time frames for completion, as presented in the Programmatic Work Plan, are shown in Table 6-3. A second tier of instream flow studies was developed by the agencies to provide future direction with regard to the conduct of the studies in the event priorities change or supplementary resources are made available to begin additional studies. The second tier includes the Guadalupe River (upper subbasin), Neches River, Red River, and Sabine (upper subbasin). It is anticipated that the time frame for completion and the order of priority of the studies are likely to change.

**TABLE 6-3 TIME FRAME FOR PRIORITY INSTREAM FLOW STUDIES**

	2003	2004	2005	2006	2007	2008	2009	2010
Lower Guadalupe River Subbasin	■	■						
Lower Brazos River Subbasin	■	■	■					
Lower San Antonio River Subbasin	■	■	■	■				
Middle Trinity River Subbasin	■	■	■	■	■			
Lower Sabine River Subbasin		■		■	■	■	■	
Middel Brazos River Subbasin			■		■	■	■	■

A comprehensive instream flow study of a stream reach or reaches is anticipated to take about three years to complete, although larger or more complex subbasins may require four or five years. These studies are subject to adverse climatological conditions and weather-related delays that can greatly affect the time frame for completion of data collection and analysis. The proposed time frame was developed to allow instream flow study elements to be carried out

<sup>10</sup> [www.twdb.state.tx.us/instreamflows/pdfs/TriAgency\\_MOA.pdf](http://www.twdb.state.tx.us/instreamflows/pdfs/TriAgency_MOA.pdf)

<sup>11</sup> [www.twdb.state.tx.us/instreamflows/pdfs/Programmatic\\_Work\\_Plan.pdf](http://www.twdb.state.tx.us/instreamflows/pdfs/Programmatic_Work_Plan.pdf)

<sup>12</sup> [www.twdb.state.tx.us/instreamflows/pdfs/TechnicalOverview-Draft080803.pdf](http://www.twdb.state.tx.us/instreamflows/pdfs/TechnicalOverview-Draft080803.pdf)

concurrently in different subbasins. The availability of study plans for multiple basins will facilitate flexible scheduling so that if flow conditions in one system are not appropriate for data collection activities, then work can take place on another subbasin.

A three-stage peer review process is incorporated into the Texas Instream Flow Studies program. The first stage, which is completed, involved an interagency science team of TPWD, TCEQ, and TWDB staff, and resulted in the Technical Overview report, which describes the methodological approach with scientific and engineering characterization and details. The second stage, which is in progress, involves an assessment of the proposed scientific and engineering methods by the National Academy of Sciences (NAS). The third stage of review will be an ongoing process that provides for the participation of various local and regional water-related authorities and other affected interests in order to ensure that local partners participate in the determination of scientifically sound findings.

The assessment work being undertaken by the NAS is through a contract with the TWDB on behalf of the three agencies, and it involves a comprehensive review and critique of the science and methods proposed for conducting the instream flow studies in Texas river basins. The Programmatic Work Plan and the Technical Overview are the two primary sources of information provided to the NAS for its review; however, the NAS has held three meetings in Texas to solicit additional information from agency staff, stakeholders, and other interested parties. The possibility exists that the NAS review committee will recommend modifications to the draft methodology or a different approach altogether for conducting the required instream flow studies. According to TWDB staff, the NAS final report is to be available before the end of 2004.

#### **6.1.2.1 TIF Study Elements**

According to the state agencies' Programmatic Work Plan, the proposed instream flow studies generally will include the following eight major study elements. While there may be some instances where an instream flow study may have fewer elements, all studies will include collection and synthesis of existing information.

1. **Study Design:** This element includes development of study objectives; determining the geographic scope of the study; identifying cooperators and their duties and tasks; and conducting reconnaissance-level surveys to identify study sites, representative stream reaches, human influences, and fish and wildlife issues. Preliminary physical and biological surveys are also necessary to provide baseline information and to help select appropriate models.
2. **Hydrologic and Hydraulic Evaluation:** This element includes development and analysis of hydrologic information and includes development of hydrologic time-series data (naturalized, historic, and predicted project flow records) and analysis of the characteristics of flow (magnitude, timing, etc.). Hydrologic models may also be developed to provide an understanding of the hydrologic network. Hydrographic surveys may be undertaken to collect data required to calibrate and verify habitat models. Complete hydrographic surveys provide the data needed to calibrate a hydrodynamic model of the stream system within the study area. A hydrodynamic model performs computer simulations of time-varying flow

through the stream segments within the study area, based on an acceptable modeling approach or technique. Such models, when properly calibrated and verified, can produce spatially explicit representations of hydraulic habitat (i.e., combinations of current velocity and depth) for a range of flow conditions (flow magnitudes). These models must be calibrated and verified, using independent data sets.

3. **Biological Evaluation:** This element requires extensive collection of biological data. Generally, biological evaluations focus on fish assemblages, but may also address other aquatic vertebrates, invertebrates, or plants. Habitat requirements, life history, and other ecological factors are addressed in order to provide input to habitat models and to provide insight in the integration and interpretation of other study elements. Specific information or models may need to be developed to address riparian habitat such as hardwood bottomlands, wetlands, oxbows, etc.
4. **Physical Processes Evaluation:** This element includes evaluations of the physical processes that form and maintain habitat, flush and transport sediment, and provide geographic information and characterization of mesohabitats, substrate, and cover (e.g., woody debris, macrophytes, undercut banks, etc.).
5. **Water Quality Evaluation:** Water quality evaluations may include analysis of existing information, but most often will require segment-specific data collection and modeling in order to relate streamflow to the environmental requirements of fish and wildlife or to water quality standards. Important water quality parameters for fish include temperature, dissolved oxygen, total dissolved solids, and turbidity. Special concerns (e.g., salt-water movement in tidal areas) may need to be addressed.
6. **Integration and Interpretation:** This element includes the integration and interpretation of information from the hydrologic and hydraulic, biological, physical processes, and water quality evaluations. Instream habitat models combine the output from hydraulic habitat models with geographic coverages of substrate and cover using geographic information system (GIS) techniques. Relationships between flow, instream habitat, and the empirically derived habitat requirements of target species or guilds are developed. A complete analysis produces a series of curves illustrating habitat as a function of streamflow. Other factors may also play into the integration, such as recreation, bay and estuary objectives, etc. Quantitative analysis performed may include a combination of statistical, optimization, time-series, and alternatives analyses. This study element also involves characterization and quantification of potential impacts to fish and wildlife resources, determinations of consequences of flow alterations, and development of instream flow recommendations. An appropriate recommendation provides a flow regime that incorporates inter-annual and intra-annual variations necessary to meet study objectives. Numerical optimization techniques will be explored in determination of the recommended flow regime.
7. **Study Report:** This element involves preparation of a study report for peer review and publication.



8. **Monitoring and Validation:** A validation of needs is required to check the results of the quantitative analysis and flow recommendations. Validation is normally accomplished by comparing the study results with information from literature and, where possible, the results from studies of similar and dissimilar streams to gauge whether the results are within the expected range. After implementation of the results in water management, it is important to continue monitoring of the stream to ensure that the implemented flow regime is meeting study objectives or baseline conditions. This will also provide information for adaptive management practices that may become necessary.

While all three cooperating agencies are expected to participate in all of the study elements and associated tasks, the assignment of a coordinating agency for certain aspects of the instream flow studies is necessary for effective project management and execution. The assigned roles reflect the respective agencies' specific expertise and their responsibilities in conservation of fish and wildlife resources and water resources management. Cooperators such as river authorities, federal agencies (e.g., U.S. Fish and Wildlife Service; U.S. Geological Survey), and others will be given the opportunity to contribute and participate in all phases of the studies.

#### **6.1.2.2 TIF Scope of Studies**

The scope of the instream flow studies as described in the Programmatic Work Plan and as put forward to the NAS includes the following five riverine components: hydrology, biology, geomorphology, water quality, and connectivity. To undertake this comprehensive scope requires an interdisciplinary approach. The evaluation of hydrology includes determinations of the characteristics of flow, such as magnitude, duration, timing, rate of change, frequency, and inter- and intra-annual variations; development of hydrologic time series (e.g., naturalized, historic, and modified flow records); and development of a hydrologic network or the geography of flows. The biology component includes development of an understanding of relationships between aquatic communities, life histories, habitat (instream, riparian, etc.), and the hydrology of the system. Geomorphology includes processes that form and maintain stream channels and habitat, flush fine sediments, and transport sediment loads. It is particularly important in studies of alluvial systems. Water quality includes temperature, dissolved oxygen, and other parameters important to survival and reproduction of aquatic organisms. Connectivity refers to the movement and exchange of water, nutrients, sediments, organic matter, and organisms within the riverine ecosystem.

Recognizing the constraints of time and resources, the state agencies believe that it will not be possible to address each of these components in a systematic or quantitative manner in each subbasin that is to be studied. However, each component should be evaluated and documented in the planning phases of each study for its applicability, feasibility, and importance to accuracy of models and study results. The planning phase may also identify important components that have not been specifically recognized in the work plan. These components may require specific attention.

As envisioned by the state agencies, an instream flow study in Texas is largely a fish and wildlife resource evaluation of a river segment, sometimes a more comprehensive subbasin evaluation, but rarely a comprehensive evaluation of an entire basin. The goals and purposes can be varied

but usually include the desire to determine the impacts of riverine flow alternations on the fish and wildlife communities.

A subbasin-specific study plan is to be developed to outline procedures appropriate for each priority study area. Given the wide diversity of aquatic ecosystems in Texas, the state's geographical vastness, and the different characteristics among and within river basins, approaches to determine instream flow requirements and predict consequences of flow alteration must be tailored to address relevant instream flow issues and sampling requirements in each system. Accepted standard procedures are to be used when available (e.g., discharge measurements, surveying, sampling, etc.) and QA/QC measures will be developed to ensure data and model accuracy. Modifications to procedures are to be validated prior to implementation. Calibrated models also are to be validated with empirical data and field observations. Study plans will guide development of scopes of work for contracts.

The study design is to be stratified to develop a prioritized series of achievable components covering all instream flow study issues (e.g., reconnaissance, baseline information, hydrology, water quality data collection and modeling, biological relationships, habitat models, riparian or wetland habitats, etc.). A set of high priority components is to form the core study elements needed for a minimal level of study. A comprehensive evaluation would include the core study elements and all supplemental (i.e., subbasin-specific) areas of inquiry and analysis. However, if external constraints (weather, resources, etc.) intervene and preclude a comprehensive evaluation, it is expected that the information necessary to complete a core analysis will be in place and available.

### **6.1.3 Critique of State Analytical Procedures for Rivers and Streams**

All of the methods used by the state for establishing instream flows for the protection and preservation of fish and wildlife resources—whether statistical desk-top analyses or comprehensive field studies and modeling—provide only an abstraction and simplification of the real and complex ecological systems in rivers and streams. With all these methods, even the comprehensive ones, uncertainty arises from the simplistic representation of the real systems, and that must be understood up front. The uncertainty manifests itself in the risk that the established instream flows are not adequate to maintain a sound ecological environment or conversely, overly protective; either being an undesired outcome.

With the statistical desk-top methods such as the CPC and the Lyons, the cause of uncertainty is transparent and hence most readily understood. With these methods, hydrology is the sole focus, and typically an interconnection of variations in streamflow, at any time scale (intra- or inter-annual), is not made to responses in the biological resources to be protected. Further, these methods prescribe instream flow regimes as fixed percentages of some hydrologic measure. The fixed percentages are not uniquely determined for each system, but rather universally applied. The lack of a river-specific connection of hydrology to the resources to be protected is both the strength and weakness of the statistical desk-top methods. The singular focus on streamflow allows these methods to be readily applied with relatively limited effort. The absence of site-specific evaluations of anything other than streamflow records, however, leaves the recommendation subject to criticism as not being responsive to the unique characteristics of each riverine system, and the findings are set and not readily amenable to negotiation. Because of the absence of interconnectivity of hydrology to river-specific fish and wildlife resources, the

application of the statistical desk-top methods should be reserved for situations where risk to and complexity of natural resources is minimal; however, this is not always the case.

The Lyons method is used extensively (almost exclusively in the absence of site-specific data) by the TCEQ for establishing environmental flow restrictions for permitting purposes; yet this method has not been even minimally validated for the wide range of streamflow and biological conditions found in Texas. Apparently, no investigations beyond those originally conducted by Bounds and Lyons in 1979 for the Guadalupe River have been undertaken for Texas rivers and streams in an effort to further validate the applicability of the Lyons method; hence, its scientific basis for application to Texas systems is quite limited. The same is true of the CPC method. While the CPC procedure has not been used by the TCEQ in water rights permitting (except for one or two instances), it nonetheless, as required by the TWDB, has been applied in planning studies of proposed water development projects. The general concept of the CPC method was developed through extensive collaboration among scientists and engineers primarily from the state's natural resources agencies, but the actual numerical criteria incorporated into the method for establishing environmental flow conditions are based more on intuition regarding environmental flow needs than site-specific field data and scientific principles.

As opposed to the statistical desk-top methods, the comprehensive methods that have been employed by the state—namely the IFIM procedures—allow river-specific assessments. These comprehensive methods attempt, at various levels of sophistication, to apply analytical methods and extensive data gathering to quantify the interconnections of hydrology with the physical and biological resources and conditions of riverine systems. Ostensibly, the comprehensive methods provide more scientifically defensible instream flow recommendations at the price of appreciably more resource commitment than the statistical desk-top methods. The more sophisticated the method—that is, the more encompassing the approach is of the pertinent processes within the riverine system—theoretically, the better the answers obtained.

While the IFIM offers the application of modern high-technology monitoring of the stream environment, it also suffers from two problems—one scientific and one operational. The scientific problem is that the method culminates in detailed measurement and modeling (either hydraulic or GIS) of the distribution of various combinations of depth, current velocity, and substrate across the streambed throughout the study reach. The correlation with the biology, at least as delineated in the present IFIM methodology, is at best tenuous. Even if the substrate/depth/velocity combinations can be used to define categories of "habitat," the relation of distribution of habitat to some measure of stream ecosystem function is not clear, nor does there seem to be a specific program to establish this relation. The suggestion that the IFIM results can be used to "optimize" flows is even more vaporous. This assumes a well-defined relation to ecology that the present method seems unlikely to produce, but further assumes that such an "optimum" bears a resemblance to the natural stream ecology. Legislation requires only that flows create a "sound ecological environment."

The second problem derives from the labor-intensive and expensive procedures of the IFIM, which means that the TIF program for carrying out instream flow studies for only six subbasins (on five rivers) will require the next seven years. The studies for a single reach of a river are projected to require three to five years, depending upon the complexity of the stream. Some intermediate course of action to address the many streams whose flows may become contentious in the meantime is needed. Such an intermediate course of action must be founded on sound data

from stream environments that include hydrological and biological observations, so there is at least the potential of establishing relationships.

The impression one might draw from the Instream Flow Programmatic Work Plan is that the state is starting from scratch collecting the necessary data. In fact, several state agencies have been collecting stream biology and habitat data since the 1970s. The TCEQ (and its predecessor agencies) have collected such data for various purposes, including discharge impact assessment (i.e., receiving water assessments), use attainability studies, routine aquatic life monitoring, least-impacted stream studies, for which fairly standard biological sampling protocols are followed. Several federal and state programs, notably TCEQ Clean Rivers Program, collect stream data following the Rapid Biological Assessment procedures. Texas Parks and Wildlife has performed biological monitoring on streams for years. Since the late 1980s, the TPWD has used such data collection (notably from the Aquatic Ecoregion project) to develop its Index of Biotic Integrity.

Because most of these data collection exercises had specific short-term purposes, most of the data are in project files or limited distribution reports. Only data collected in the last several years is in digital form, and even that is in special-purpose formats, such as worksheets. The state should be encouraged to mount a comprehensive review and digitization project to recover all of this data and make it available to stream ecologists and other scientists. This can be done at a fraction of the cost of one of the IFIM field studies, and may create a data set for at least some of the streams in Texas that might allow the relation between flow and ecosystem function to be evaluated. At a minimum, this data might prove useful in validating (or invalidating) either the Lyons or the Consensus Planning Criteria approaches.

The key to success of any comprehensive method is the necessary commitment of resources to minimize knowledge uncertainty—wherein knowledge uncertainty arises for an incomplete understanding of the system and inadequate measurement of the system. If this resource commitment is not made, comprehensive methods offer no advantages over standard-setting methods, and in fact, less reliable instream flow recommendations may result because knowledge uncertainty will be excessive. With proper resource commitment, comprehensive methods offer the definite advantage of providing location-specific recommendations that consider interconnections of hydrology with the resources to be protected.

Indeed, the Texas Instream Flow Studies methodology as currently structured and planned by the state agencies in response to Senate Bill 2 incorporates state-of-the-art models and data collection procedures found in the more advanced comprehensive methods. The proposed procedures and analyses appear to offer an approach for establishing environmental flows for rivers and streams across the state that can be scientifically based and reflective of the varying relationships between hydrology and the physical and biological conditions in different systems. Rigorous basin or site-specific post validation will be critical to establishing the robustness and validity of the methodology.

The question remains as to exactly how this program will be carried out and applied in a specific basin or subbasin and how the results will be used to finally establish the appropriate values and conditions of streamflows for effectively protecting instream environmental uses. From the outset, this process has to effectively involve all stakeholders and interest groups, not just the three state agencies responsible for devising and implementing the program, and it must be subjected to rigorous scientific review. The development of appropriate environmental flows for

a particular river or stream has to encompass the proper science in accordance with the state agencies' proposed program, as well as the input of local and regional interests in order for effective and acceptable results to be achieved. In effect, the appropriate science has to be applied and has to filter down from the state agencies, while the goals and objectives for satisfying basin- or subbasin-specific environmental flow requirements has to migrate up from river and stream users. This is of paramount importance.

#### **6.1.4 Methods Used Outside of Texas for Rivers and Streams**

The Instream Flow Council (IFC) has compiled one of the more comprehensive evaluations of available tools for assessing environmental flows in rivers and streams (Instream Flows Council, 2002). The IFC evaluated more than 30 flow assessment tools that are in use elsewhere throughout the United States. The 30 tools are grouped into three broad categories, namely "standard setting", "incremental", and "monitoring/diagnostic". Standard setting methods are those that typically involve application of the desk-top, rule-of-thumb methods for setting limits below which water cannot be diverted or stored. The incremental techniques involve "site-specific analyses that examine multiple decision variables and enable different flow management alternatives to be explored", similar to the comprehensive methods described above. The monitoring/diagnostic methods involve field studies to collect data and assess ecological conditions as they may change over time to provide the information necessary to allow the implementation of corrective measures, as required. Other recent reviews of commonly used environmental flow methods include Annear and others (2002, U.S. and Canada); Tharme (2003); and Dyson et al. (2003, global).

Which approach (or approaches) is used for evaluating environmental flows is often tied to the level of risk to fish and wildlife resources, issue complexity, the nature of the aquatic system, available resources and expertise, and the level of controversy associated with a particular project. For low-risk situations with minimal complexity, the desk-top (standard setting) methods are more likely to be applied. In the more complex cases where analysis of trade-offs is desired, then the incremental or comprehensive methods are typically used.

Most statistical desk-top methods typically use historical hydrologic data (annual, monthly, or daily flow records) to establish minimum flows for protecting instream uses. These flows are often based on a fixed percentage of a central tendency hydrologic statistic (e.g., 40% of the mean annual flow) or a percentile flow from a flow duration curve (e.g., 25<sup>th</sup> percentile). Texas' default methodology, the Lyons method, is this type of method derived from the Tennant method. The Tennant method (aka, Montana method) is an example of a statistical desk-top method that is used in a large number of western states and Canadian provinces (16 in 1989). According to Tharme (2003), it has become the most commonly applied statistical desk-top (hydrological) method globally. Based on field measurements, photographs, and flow records from 11 streams in three states (Montana, Wyoming, and Nebraska), Tennant specified different percentages of the average annual flow (AAF) to provide for different habitat objectives (optimum, outstanding, excellent, good, fair, poor, and severe degradation) for two time periods within an annual cycle. For example, for outstanding habitat, 40% AAF is used for October-March and 60% AAF is used for April-September, while values for fair or degrading habitat are 10% AAF for October-March and 30% AAF for April-September. Flushing flows are also specified as 200% AAF for 48 to 72 hours. Tennant substantiated these findings on a wide variety of streams, including brooks, prairie streams, and coastal plains streams located in 21

different states. Other desk-top methods include: Aquatic Base Flow (New England region); wetted perimeter (Michigan and Montana), R2-cross (Colorado and Wyoming), and other transect-based hydraulic rating methods; and standards for maintaining water quality, such as the seven-day, ten-year low flow (eastern and southeastern states).

As noted by the Instream Flows Council (2002), “the word ‘standard’ came to mean ‘minimum’—a line in the sand (sometimes literally) above which all water could be appropriated and below which the water was reserved for aquatic life.” It is generally agreed that such a flat-line flow regime cannot account for all of the important interrelationships between the streamflow, biology, and physiography along a particular stream reach. The common criticism of standard setting methods is their lack of site specificity regarding these types of relationships.

Incremental or comprehensive techniques normally involve data collection and the use of site-specific analyses and modeling to examine multiple decision variables and their relationships to different flow regimes. Incremental methods often require intensive field studies by experienced and trained personnel. These methods are often used when water supplies are limited and there are competing demands for water to meet human needs and environmental requirements. Aside from the IFIM described above, other comprehensive instream flow methods for rivers and streams include: MESOHABSIM (northeast United States), RHY-HABSIM (New Zealand), CASI-MIR (Europe), Building Block Method (South Africa), the Holistic Approach (Australia), the Range of Variability Approach (United States, Canada, and South Africa), and the Riverine Community Habitat Assessment and Restoration Concept (United States).

One of the more documented efforts to establish environmental flows for a combined riverine and estuarine system is the Savanna River program that is currently being undertaken jointly by the U. S. Army Corps of Engineers (Corps) and The Nature Conservancy (TNC) under protocols developed by the TNC’s Ecologically Sustainable Water Management (ESWM) program. These include the use of a desk-top method for establishing initial environmental flow values, an expert panel to review results and make decisions regarding what measures to implement, and adaptive management procedures to address scientific allowances for uncertainty.

The ESWM program involves a seven-step process derived from methods developed for the Flint and Apalachicola watersheds of Georgia, Alabama, and Florida (Richter, et al. 2003). The Savannah River project utilized a six-step ESWM program in which human needs for water are met by storing and diverting water in a manner that can sustain or restore the ecological integrity of affected river ecosystems. The six steps are:

1. Define ecosystem flow requirements using a statistical desk-top method that produces a comprehensive Index of Hydrological Alteration (IHA) and develops initial numerical estimates for a Range of Variability Analysis (RVA) of key aspects of river flows that are potentially implicated to sustain native species and natural ecosystem functions.
2. Determine the influence of human activities accounting for human uses of water, both current and future, through development of a computerized hydrologic simulation model that facilitates examination of human-induced alterations to river flow regimes.

3. Identify areas of incompatibility between human and ecosystem water needs with particular attention to their spatial and temporal character.
4. Search for collaborative solutions to resolve incompatibilities.
5. Conduct water management experiments which are designed and implemented to resolve critical uncertainties that frustrate efforts to integrate human and ecosystem needs.
6. Design and implement an adaptive management plan using the knowledge gained in Steps 1–5 to facilitate ecologically sustainable long-term water management.

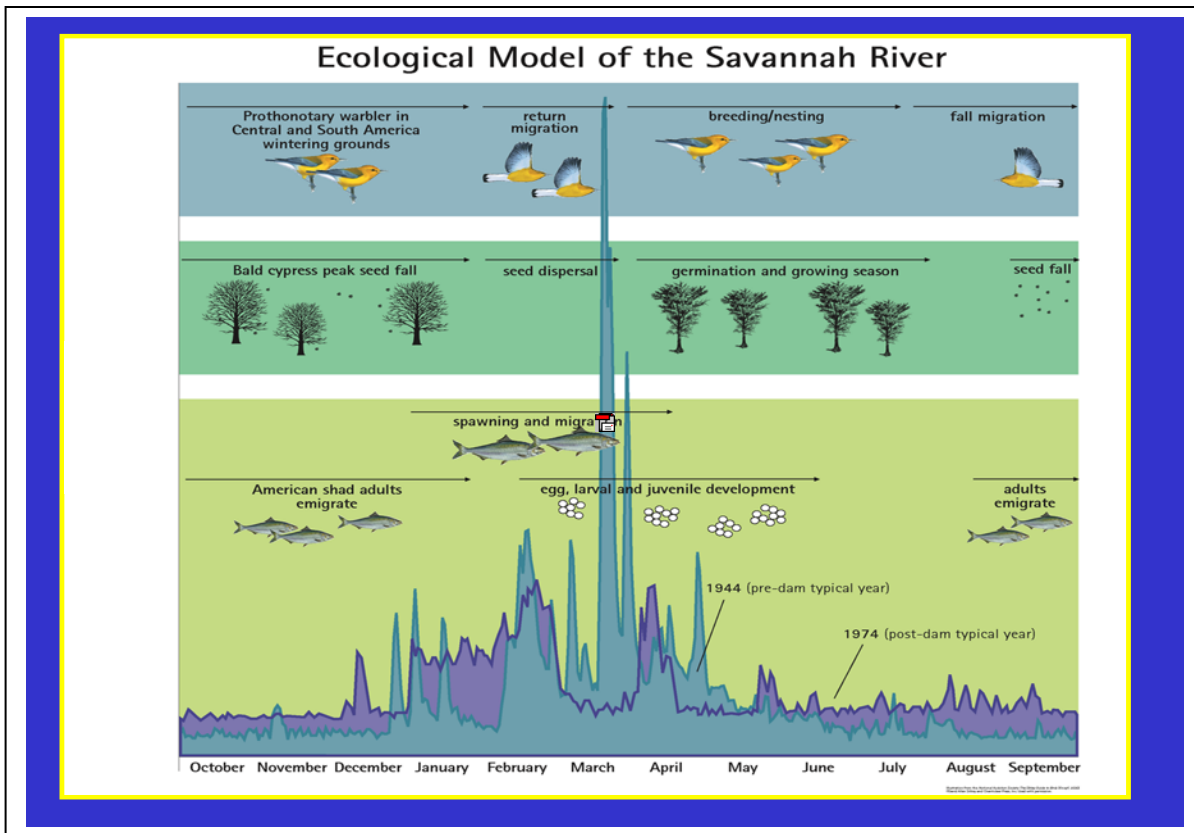
The Savannah River case extended this framework to maintenance and restoration of the biological soundness of the Savannah River of Georgia and South Carolina. There, the Corps and the TNC combined the desk-top analysis, expert panel, and adaptive management increments into a single, sequential process. This method formulated and tested initial flow linkage prescriptions and potential incompatibilities, using protocols developed by the TNC's ESWM program. The Savannah River case addressed an array of connected ecotypes and flows regimes—inland rivers, wetlands, bays, and estuaries.

Statistical desk-top modeling was applied to naturalized and historically gaged flows of the Savannah River to yield a suite of more than 60 indices of hydrological alteration (IHA) and ranges of variability analyses (RVA). The environmental flow results from the desk-top analysis were treated as “place holders” for follow-on expert functional analysis of their site-specific ecological significance.

The expert functional analysis process for Savannah River, as described by Richter and others (2004, in press), included conferences and workshops composed of a wide array of scientific expertise—including biological, geological, hydrological, and water quality. The approach used was to have this group report on their scientific consensus on pertinent issues.

The conference and workshop processes were underpinned by extensive ecological literature searches and technical summaries produced by the local academic center, the University of Georgia. Broad technical group recruitment and consensus mechanisms were intentionally designed to mitigate the potential effects of individual interest or bias. Important questions that could not support consensus were deemed uncertainties, to be subjected to later research, testing, or adaptive management. The resulting initial variable flow prescriptions for the Savannah River were based on the best available scientific literature and the collective expertise regarding the life cycle and flow linkages of many different species, such as those summarized in Figure 6-4.

Expert flow-prescription recommendations were accompanied by a program for testing of initial assumptions and uncertainties, and adaptive management techniques were incorporated to identify incompatibilities and policy options to resolve them. This particular combined methodology yielded initial flow prescriptions for three different flow levels (low flows, high flows, and over-bank floods) for each of three separate annual climatic scenarios (drought, average, and wet years).



**FIGURE 6-4 SIMPLIFIED FLOW LINKAGE DEPICTION FOR SAVANNA RIVER**

Between the extremes of simple statistical desk-top (standard setting) methods and intensive, site-specific comprehensive (incremental) methodologies for evaluating environmental flows, there is a group of modalities labeled as “mid-level” monitoring/diagnostic methods by the Instream Flows Council (2002). These range from rapid or desk-top methods to more intensive site-specific methods. The more intensive of the monitoring/diagnostic methods is the Index of Biotic Integrity (IBI) sometimes used by agencies in Texas. A rapid or desk-top monitoring/diagnostic method is the TNC’s combined Index of Hydrological Alteration (IHA) and Range of Variability Analysis (RVA). This was the approach which formed the initial analytical basis for the Savannah River incremental process.

Using TNC’s IHA software, the statistical characteristics of low flows, high-pulse flows, floods, and even extremely low flows can be readily computed from a historical record of daily flows, or from model-simulated daily flows. The IHA software first categorizes each daily flow value as a low flow, high-pulse flow, etc. The IHA software will then generate ecologically relevant flow statistics, such as the magnitude of low flows that occur in each month, the frequency of high-pulse flows that occur during the year, and the size and duration of floods, etc. Using these statistical summaries, appropriate instream flow targets can be determined. For example, based upon the magnitude of low flows that have occurred historically in January, an instream flow target for January could state that low flows in the month must fall within the 0-33<sup>rd</sup> percentile during one third of the time; between the 34<sup>th</sup> and 66<sup>th</sup> percentile in another third of the time; and at or above the 67<sup>th</sup> percentile in other years. The Nature Conservancy has named this instream flow targeting method the Range of Variability Approach, or RVA (Richter et. al. 1997).



The RVA can be implemented through either a retrospective, or a predictive process. In a retrospective process, actual river flows are monitored over the course of a year. At the end of a year or series of years, water managers can then evaluate whether the instream flow targets were met. For example, did January low flows fall within the 0-33<sup>rd</sup> percentile during one-third of the time, between the 34<sup>th</sup> and 66<sup>th</sup> percentiles during one-third of the time, and at or above the 67<sup>th</sup> percentile during the remaining time? The great disadvantage of this approach is that any violations to instream flow targets will be detected only after the fact, making it very difficult to enforce their protection.

A far more preferable approach is to implement the RVA's instream flow targets using a predictive modeling-based approach. A computer simulation model is constructed to represent the natural flows and the influence of all significant water diversions or other human activities (e.g., dam operations) on the flow conditions in a river. This is similar to the Texas WAM, except that the WAM runs on monthly time steps instead of the daily time steps required to implement the RVA. Using such a model, water managers could evaluate whether a proposed water withdrawal or the operation of a proposed dam will violate the RVA-based instream flow targets and make permitting decisions accordingly.

## **6.2 Bays and Estuaries**

### **6.2.1 State Analytical Methodology**

The state of Texas chose many years ago to employ a detailed “quantitative” analytical method regarding determination of appropriate bay and estuary inflows. Development of a quantitative methodology for determining necessary inflows to the Texas bays has been undertaken primarily by the TWDB and TPWD. The TWDB has assembled data bases of water budgets for the Texas bays, their water quality and physiography, and commercial harvests of key species, which are used as a measure of ecological health. In addition, TWDB has developed mathematical models of various aspects of the Texas bays, including inflows due to ungauged runoff, circulation, and salinity distribution, and has sponsored academic research on various aspects of their ecology. TPWD has conducted intensive biological collections in the Texas bays, using a variety of sampling equipment, since (in some of the bays) the early 1950s. Since approximately 1985, in response to several legislative directives, the two agencies have coordinated their respective programs. Though they jointly operate a study program focused on determining the needs for freshwater inflows to the Texas bays and estuaries, their respective activities and responsibilities continue their historical pursuits.

One of the major determinations of the freshwater inflow studies is 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 for a bay under consideration is carried out in two steps. The first step, conducted by the TWDB, is the application of a quantitative methodology to determine optimal inflows to that bay that will achieve one of several specified management goals. The second step, conducted by the TPWD, is to select that inflow solution considered to best achieve the purpose of maintenance of ecological health and productivity. The method employed in the first step is referred to as the State Methodology, in deference to the joint responsibilities of the

two agencies, while the procedure of the second step is referred to by the TPWD as "verification" that the State Methodology solution in fact will protect that bay's ecological health.

The State Methodology is documented in an extensive report (Longley 1994). The series of data analyses, calculations, and model operations making up the State Methodology is diagrammed in Figure 6-5. The answer from this process is a pattern of monthly freshwater inflows to a bay or estuary that are required to maintain the estuarine ecosystem.

Despite the apparent complexity of the State Methodology, only a small subset of the calculations determines the answer—namely those elements enclosed by the bold blue outline on the diagram in Figure 6-5. Most important of these is the relation of ecological health to freshwater inflow. Ecological health is measured by the abundance of a few key species (e.g., brown shrimp, blue crab, and red drum), abundance in turn being estimated by the commercial harvest of the key species (or, in the most recent determinations, by traditional biological collection data). Statistical relations are developed between harvest (or, in the most recent applications, effort-normalized collection data) and "seasonal" inflows. In addition, statistical relations are established between measured salinities at key locations in the bay and monthly inflows. By adding the predicted harvests (or normalized catch) of the key species, a predicted total abundance is determined that depends upon the seasonal inflow values. ("Seasonal" can refer to either monthly-total or bimonthly-total flow, depending upon the relation.) An optimization model is then used to determine the distribution of monthly inflows that either maximizes or minimizes some variable, defined by a specific management goal. While several management goals are typically evaluated, the most important are:

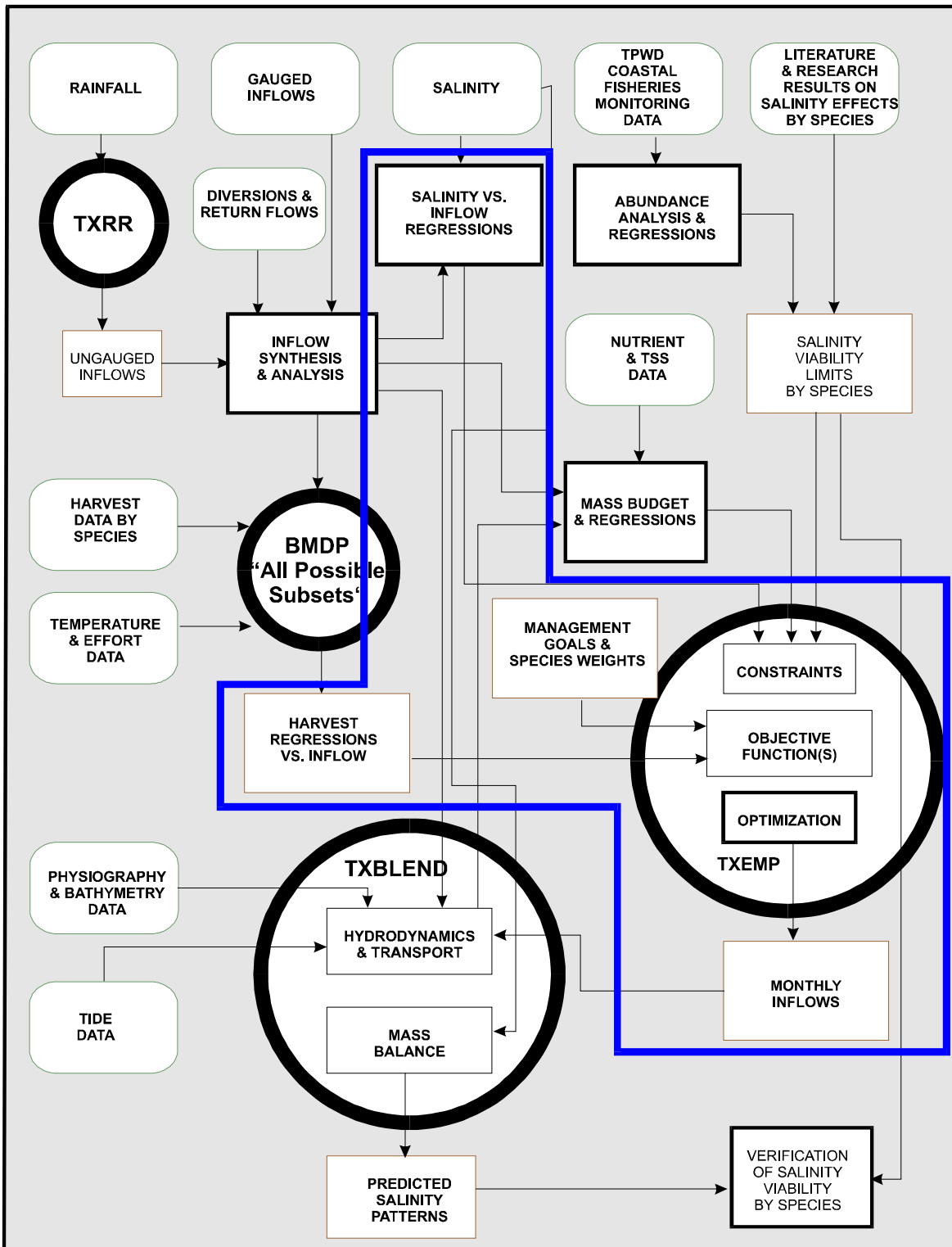
*maxH* total annual harvest is maximized, subject to constraints that the monthly inflows be bounded by the lowest decile and median period-of-record flows for each month

*minQ* total annual inflow is minimized, subject to the constraint that total annual harvest be no lower than 80% of its period-of-record average

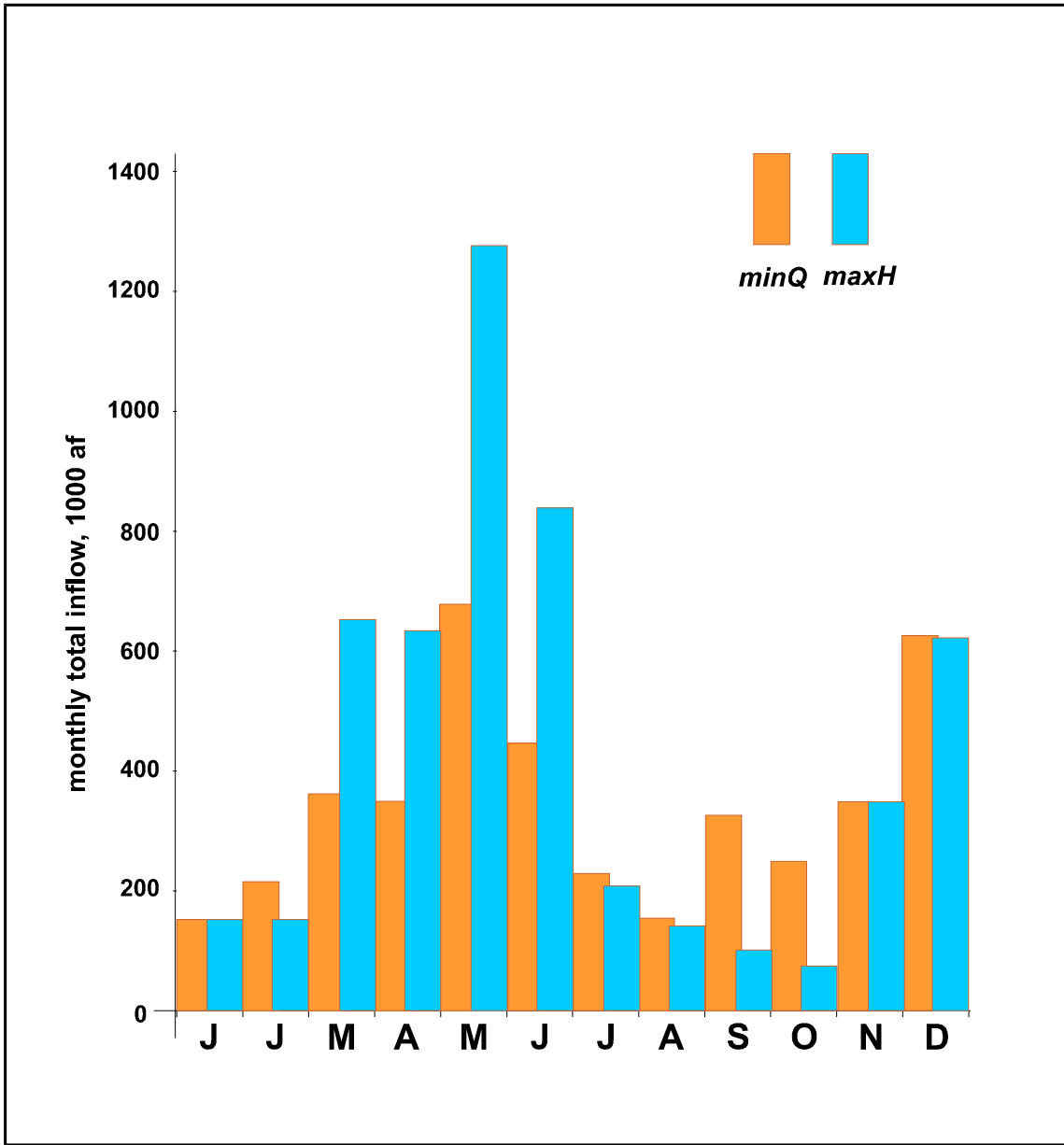
(In the latest determinations in which biological-sampling catch rather than harvest is used as a measure of abundance, the corresponding optimum is designated *maxC*.)

Both *maxH* and *minQ* monthly flows are shown in Figure 6-6 for Galveston Bay. (Other constraints may be imposed, such as the requirement that salinities—as determined from monthly inflows using the statistical relation—lie within the known tolerance limits for the key species.) The Longley (1994) report presents the State Methodology as a case study of its application to San Antonio Bay. Applications to the other six major estuaries of the Texas coast (Sabine Lake, Galveston Bay, Matagorda Bay, Aransas-Copano Bay, Corpus-Christi Bay, and the Laguna Madre) have been documented by supplemental technical memoranda issued by the TWDB staff, except for Matagorda Bay, to which the application of the State Methodology was performed by the LCRA.

The TPWD undertakes a separate evaluation to select among the flows obtained from the State Methodology for different management goals. This procedure is described by TPWD as an "evaluation of inflow solutions to verify that inflow levels produced by models will maintain ecological health and productivity." The TPWD emphasizes that this is carried out using



**FIGURE 6-5 DIAGRAM OF STATE METHODOLOGY FOR DETERMINING FRESHWATER INFLOW NEEDS FOR BAYS AND ESTUARIES**



**FIGURE 6-6 PATTERN OF MONTHLY FRESHWATER INFLOWS RESULTING FROM APPLICATION OF STATE METHODOLOGY**

independent physical and biological data collected by the agency, principally through its Coastal Fisheries monitoring program, and refers to it briefly as a "verification." It is more difficult to summarize the TPWD methodology than that of the State Methodology, for two reasons: there is no general technical description of the procedure analogous to the Longley (1994) report, and the bay evaluations are presented in brief "executive-level" documents with only a fraction of the supporting analyses upon which TPWD bases its selection. These evaluations have thus far included:

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.

Individual reports have cited instances of oyster disease, increased predation by marine organisms, and marsh inundation, in *ad hoc* and qualitative arguments to further support the selection of inflow regime options.

Determination of the pattern of beneficial inflows involves the separate but coordinated actions of the TWDB and TPWD. Since 1990, the TWDB has set about applying the State Methodology to establish the monthly beneficial inflows for several management goals for each of the seven major bays of the Texas coast, in this order: San Antonio Bay, Aransas-Copano Bay, Matagorda Bay, Galveston Bay, Upper Laguna Madre, Lower Laguna Madre, Corpus Christi-Nueces Bay, and in draft form, Sabine Lake. For each set of results on a given bay, the TPWD has further evaluated the inflow patterns using its procedure, to eventually select the pattern corresponding to one of the management goals, designating this pattern the "beneficial" or "target" inflows for that bay. While the time varies, approximately a year is required between completion of the TWDB application of the State Methodology and the designation of one of the State Methodology patterns as the beneficial inflows. At this point, the TPWD has issued final recommended beneficial-inflow determinations for: San Antonio Bay, Galveston Bay, and Corpus Christi-Nueces Bay. The LCRA, working cooperatively with the TPWD and TWDB, issued a report documenting the Matagorda Bay beneficial-inflow determination. Draft recommendations have been provided for Upper and Lower Laguna Madre and Sabine Lake. Table 6-4 presents a summary of these monthly recommended freshwater inflows for the various bay systems. As shown, different management goals have been used as the basis for establishing the recommended inflow regimes for the different bays and estuaries, i.e.,  $maxH$ ,  $minQ$ , etc. In terms of relative quantities, the recommended annual inflow amounts for the different bay systems range from about 10% to 70% of the corresponding historical average flows.

**TABLE 6-4 SUMMARY OF RECOMMENDED FRESHWATER INFLOW REGIMES FOR TEXAS BAYS AND ESTUARIES**

Month	Final Recommended Freshwater Inflows									Draft Recommended Freshwater Inflows					
	Galveston Bay Trinity-San Jacinto Estuary			Matagorda Bay Lavaca-Colorado Estuary		San Antonio Bay Guadalupe Estuary		Corpus Christi Bay Nueces Estuary		Sabine Lake Sabine-Neches Estuary		Baffin Bay Upper Laguna Madre Estuary		South Bay Lower Laguna Madre Estuary	
	MinQ Flow ac-ft	MaxH Flow ac-ft	Hist. Average Flow ac-ft	Target Flow ac-ft	Hist. Average Flow ac-ft	MaxH Flow ac-ft	Hist. Average Flow ac-ft	MaxH Flow * ac-ft	Hist. Average Flow ac-ft	MaxC Flow ac-ft	Hist. Average Flow ac-ft	MinQ Flow ac-ft	Hist. Average Flow ac-ft	MinQ Flow ac-ft	Hist. Average Flow ac-ft
Jan	150,500	150,500	900,903	94,200	216,517	111,200	159,824	2,230	20,566	1,246,400	1,699,493	2,080	8,047	16,230	25,194
Feb	216,700	155,200	929,369	100,200	235,753	124,200	176,908	2,780	22,679	1,539,200	1,656,024	1,550	8,759	16,020	25,164
Mar	363,900	652,800	927,065	195,900	204,921	52,420	152,252	4,920	18,131	1,565,780	1,747,327	1,260	5,654	16,690	18,135
Apr	352,600	632,500	1,038,525	252,100	249,085	52,420	200,956	5,180	27,508	1,136,640	1,603,790	1,200	9,018	19,170	31,234
May	679,700	1,273,700	1,522,301	298,700	405,611	222,600	296,814	37,770	88,332	691,900	1,705,158	1,520	18,119	26,250	38,422
Jun	448,100	839,700	1,218,681	289,500	395,918	162,700	296,820	36,430	86,796	478,700	1,255,322	2,010	12,955	22,090	39,424
Jul	232,700	211,500	632,396	194,600	219,346	88,610	156,689	9,820	50,894	547,300	816,456	1,750	12,847	18,100	24,705
Aug	154,000	140,000	379,458	100,200	119,500	88,330	114,014	9,750	39,751	466,500	492,080	1,730	15,576	15,030	27,825
Sep	330,200	103,000	533,187	151,400	326,460	52,420	244,917	9,600	113,328	574,600	574,623	1,490	40,534	15,900	84,718
Oct	251,900	78,600	538,943	141,700	301,157	52,420	227,510	7,560	90,650	537,900	537,906	3,480	26,296	17,170	69,594
Nov	351,500	351,500	651,704	92,600	217,135	73,830	169,135	7,780	26,200	237,550	618,738	1,720	5,201	16,930	30,648
Dec	626,800	626,800	768,678	89,000	188,897	66,200	148,301	4,670	13,291	574,130	1,102,491	1,770	10,378	15,370	19,480
Annual	4,158,600	5,215,800	10,041,210	2,000,100	3,080,300	1,147,350	2,344,140	138,490	598,126	9,596,600	13,809,408	21,560	173,384	214,950	434,543
% of Hist.	41.4%	51.9%	--	64.9%	--	48.9%	--	23.2%	--	69.5%	--	12.4%	--	49.5%	--

\* For Corpus Christi Bay/Nueces Estuary, when the the cumulative April-July MaxH flows have not occurred, then the cumulative MinQ target flows (27,510 acre-feet) should be provided during September-November.

MinQ: Total annual inflow is minimized, subject to the constraint that total annual harvest be no lower than 80% of its period-of-record average.

MaxH: Total annual harvest is maximized, subject to constraints that the monthly inflows be bounded by the lowest decile and median period-of-record flows for each month.

MaxC: Total annual fisheries productivity (maximum catch) is maximized, subject to monthly maximum and minimum boundaries corresponding to minQ and maxQ.

Hist. Average Flow = Historical average flow for period of record generally extending from early 1940s through mid-1990s.

Application of the beneficial-inflow results remains problematical. First, under present law, releases from reservoirs to meet inflow needs of the bays and estuaries are required only for reservoirs built within 200 river miles of the coast on or after September 1, 1985. Only two such reservoirs have been built, namely Lake Texana on the Navidad River and Choke Canyon Reservoir in the Nueces basin. Both of these antedated the State Methodology applications of the TWDB; hence, these results were not used in developing the operating plans for these reservoirs. (For Choke Canyon, the earlier State Methodology results—from application of the 1980 version of the methodology—were used to establish the Interim Order release schedule for the tandem operation of the Lake Corpus Christi-Choke Canyon Reservoir system. This involved releases from storage to make up the monthly deficit in meeting the desired pattern of monthly inflows to Nueces Bay. This operating plan has subsequently been replaced by a pass-through schedule.) Second, according to law, for reservoirs built with state funds, 5% of the reservoir yield is reserved for bays and estuaries needs. But the beneficial-inflow levels for the Corpus Christi-Nueces system and for Matagorda Bay, apportioned to the new reservoirs, far exceed this commitment of yield.

## **6.2.2 Critique of State Analytical Procedures for Bays and Estuaries**

As previously summarized, the determination of target or beneficial inflows to a Texas bay is a two-step procedure: (1) the TWDB applies the State Methodology to compute annual sequences of monthly inflows that will achieve several standard optimization goals, notably *minQ* and *maxH*; and (2) TPWD applies a "verification" analysis to select that annual sequence of monthly inflows that best achieves the protection of the health of the bay ecosystem. Both steps are represented by the agencies as being established scientific methods, and the procedure has even been described as the "best available science." (McKinney 2003)

First consider the State Methodology. This falls in the realm of applied science, and consonant with the purpose of providing an answer to a specific question of concern to society, it has proved necessary in the State Methodology to relate variables by seeking statistical associations, absent a suitable theory. As diagrammed in Figure 6-3, several of the important relationships are based upon statistical analyses, such as the relation of salinity in the bay to monthly inflows and, especially, the relation of abundance of key species to bimonthly flows. These relationships are the core of the methodology and form the basic input to the optimization model (TXEMP) used to determine the monthly flows for *maxH* and *minQ*. There are several deficiencies in the analyses of the TWDB including: (1) commercial harvest, which is the basis for these determinations prior to 2003, is an inadequate measure of abundance, because it is influenced—even dominated—by factors that are unrelated to the abundance of the organism, such as market price, operating costs, and regulation of the fishery; (2) the statistical methods are rather simple, compared to the complexity of the behavior of estuary organisms, and do not evidence satisfactory explanatory power; (3) the characterization of inflow by bimonthly sums, and the selection of these sums as independent variables are questionable; (4) the optimization solution is over-constrained by the limits on the range of monthly flows, and it is these limits, rather than the behavior of the relationships of harvest on flow, that primarily dictate the answer; and (5) there is no justification provided for the selection of these bounds (lower decile to median) on monthly flows.

More significantly, it is not clear that seeking an optimal solution, even if it can be correctly obtained, is the right answer to the question. The computed optimum flows far exceed the usual low-flow and *a fortiori* drought conditions in the bays. The optimum solutions obtained for the major bays of Texas involve annual flow volumes that exceed the cumulative storage of all reservoir projects in the basin, so it is not clear how these projects could be operated to meet this flow, were that the intention. Moreover, the optimum sequence of monthly flows does not occur in the historical flow record (i.e., for no year in the record are all, or even a majority, of the measured monthly flows within even  $\pm 20\%$  of the *maxH* values). The implication is that a satisfactory level of ecosystem health of the Texas bays has been maintained, even though the natural flows have been considerably "off the optimum." The question of what flows (volumes and seasons) are *necessary* for the maintenance of that health has not been addressed.

Despite these criticisms, it must be borne in mind that the present State Methodology is the product of over three decades of effort by the TWDB, dating back to the late 1960s. The state justifiably has been praised for its vision in addressing the issue of inflows to the bays, and has pioneered the application of quantitative, science-based methods. Nor is it inconsistent to acknowledge the state's prescience in formulating a scientific approach to the problem and the contributions it has made to estuarine science in pursuing that approach, while criticizing the validity of the approach or the accuracy of the results. In science, there are many instances of important concepts or procedures that ultimately proved to be wrong. It is interesting to observe that the present State Methodology does not differ substantially from its predecessor work published in the 1970s–1980s (e.g. TDWR 1979).

The "verification" analysis of the TPWD is documented as a "freshwater inflow recommendation" for the bay that "critically evaluates" the TWDB optimization analysis, characterized as "a range of flows necessary to maintain an 'ecologically sound and healthy' environment" within the bay (quotes from Pulich et al. 2002). Typically, the *minQ* and *maxH* monthly inflows are used to drive the two-dimensional circulation model TXBLEND that then produces a simulation of salinity at a grid of points throughout the bay every two hours over the one-year simulation. This simulated time history of salinity is then compared to the estimated upper and lower limits on salinity required for viability of the key species. The same model predictions are used to determine the horizontal area enclosed between the upper and lower salinity species *preference* limits for key months—the implication being that the inflow regime producing the highest simulated area is most beneficial for the ecosystem. The species preference limits are determined from an analysis of the salinities accompanying the catch of that species in the TPWD Coastal Fisheries data.

While there are many aspects of this protocol that are technically debatable, the procedure suffers from two major failings. First, it relies upon the TXBLEND salinity predictions for much of the analysis. This model does not have the acceptance of other available models that have been widely and successfully applied to estuaries. The model has not been satisfactorily validated for Texas estuaries (though it has been adjusted to replicate observed salinities, i.e. "calibrated"). Second, the TPWD protocol emphasizes the differences between *minQ* and *maxH*, but does not address the question of what flows are *necessary* for maintenance of the health of the bay (flows that are probably keyed to season).

The employment of the intensive catch data of the TPWD Coastal Fisheries monitoring program is admirable. This data collection program, in which a variety of gear is used to rigorously



sample the organisms present in each of the Texas bays, has been underway for decades, and is a magnificent resource for the study of these estuaries. The TPWD is to be commended for its vision and resolve in implementing and maintaining this important data-collection program.

Both steps of the state analytical procedure suffer from an additional major scientific deficiency: they are inadequately documented and incapable of corroboration. The statistical results of the State Methodology are documented in Longley (1994) and as appendices for the individual bay analyses. None of these includes the data upon which the analyses are based. (The data sets are provided by the TWDB upon request.) The statistical procedures are incompletely described, and it has emerged recently that this documentation for some of the past studies, such as Galveston Bay, has been lost. The TPWD "verification reports" are presented in summary form, with a selection of the results to indicate the method. For at least some of the bays addressed in the past, basic supporting analyses have been lost. Finally, TXBLEND, the hydrodynamic-salinity model that is a key element of the TPWD analyses, for much of its period of use by TWDB and until recently, could not be released to the public, including other scientists, because it contained proprietary computer codes.

Although it is probable that the high-flow months (typically spring and fall) are of major importance to estuary ecosystem function, it is also well known that low flows, especially the prolonged low flows of a drought, can stress that ecosystem. Under low-flow conditions, the diversion of water for inland uses or its capture in reservoirs can substantially reduce even further the inflow into a bay. Moreover, permitting and regulation of inland water resources in Texas is couched in the context of drought, such as the determination of firm yield. The low-flow condition should, therefore, be a priority for determination of the effect on the ecosystem and requirements for its maintenance. Yet, the state analytical procedure—because both the TWDB and TPWD procedures address only the much higher flows of the optimum conditions (*minQ* and *maxH*)—fail to provide any information about the important low-flow regime. Considering that the agencies have had decades to address the problem of freshwater inflow needs, this omission is inexplicable.

### **6.2.3 Methods Used Outside of Texas for Bays and Estuaries**

Government officials and the public have increasingly asked estuarine scientists and resource managers two basic questions: What are the minimum inflows needed to protect estuarine health? How can existing water projects be operated to minimize damaging alterations of inflows to estuaries? Given this strong interest over the last 30 years, the number of dedicated scientific symposia that resulted in written documents on the subject has been amazingly few. Although there have been numerous conferences, special sessions, and symposia on the topic, there have been only two that resulted in published documents.

The first symposium and compilation of papers on the topic of freshwater inflows was organized by Cross and Williams (1981). That symposium was convened to identify the issues regarding freshwater inflow to estuaries and identify potential solutions and recommendations to deal with the issues. Since the original symposium in 1981, the problems and issues related to freshwater withdrawal have increased with increasing water resources and coastal development and increasing environmental awareness, but progress in terms of understanding the relationship between inflow and estuarine resources has been made.

The second symposium and compilation of papers was organized by Montagna et al. (2002). The session started with papers describing different approaches for estimating freshwater input to estuaries, identifying ecological resources or indicators of inflow effects, and setting freshwater requirements. The symposium volume contains many case studies that were international in scope and included estuaries in Australia, South Africa, and the United States. The studies in the United States were also broad and included California, Texas, Georgia, and Florida. On one hand, there is no single method or approach to either evaluate inflow needs or set minimum inflow levels. However, what emerges is a comprehensive review of the state of the science and commonality in approaches used in several geographic regions. It is likely that combining the recent scientific advancements with the common approaches will lead to new and better tools for assessment. The description of case studies below is taken largely from this symposium, especially reviews by Alber (2002) and Estevez (2002).

**6.2.3.1 Florida, U.S.A.** - The state of Florida is a very diverse state hydrologically, and is divided into the following five different Water Management Districts (WMD) that are responsible for water resources within their boundaries:

- Northwest Florida Water Management District (NWWMD)
- St. Johns River Water Management District (SJWMD)
- South Florida Water Management District (SFWMD)
- Suwannee River Water Management District (SRWMD)
- Southwest Florida Water Management District (SWFWMD)

Although the WMDs were established by the Florida Water Resources Act of 1972, it was not until 2000 that legislation required establishing minimum flows and levels for all surface waters and aquifers. The minimum flow is defined as the “limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area.” In general, the steps to develop minimum flow levels (MFLs in Florida jargon) include identifying water resource functions, defining significant harm, and providing standards to protect these functions from significant harm. Because of the diversity of ecosystems in Florida, the WMDs are taking a variety of approaches to develop MFLs, and there is an enormous number of examples of how the MFLs are being established. Here, only two contrasting examples are discussed.

The SWFWMD uses a flow-based management approach. In the late 1980s, the district created the “10% presumption rule” for reviewing water withdrawal permits. This rule was based on the assumption that water withdrawal will not cause unacceptable environmental impacts if it does not reduce the rate of daily flow by more than 10%. Some scientific research has shown that this is the case for rivers and streams (Flannery et al. 2002). This approach emphasizes the interaction of inflow with stationary and dynamic habitat components. Organisms move upstream or downstream as flow rates decrease or increase, so they are in synchrony with the dynamic nature of the habitats. The approach prevents harmful impacts during low flow periods and allows water supplies to become more available as flows increase. The percent-of-flow approach works in the SWFWMD because there are six streams and rivers feeding Tampa Bay, seven streams and rivers feeding Charlotte Harbor, and rainfall is high (averaging 1.35 meters/year, or about 53 inches/year). Ongoing efforts are focused on refining the percentage withdrawal limits on a seasonal basis, because seasonal processes such as phytoplankton production and fish recruitment can be harmed at the 10% level during dry periods.

The SFWMD employs a resource-based flow management approach. Rather than focusing on commercially important species, as Texas does, the SFWMD approach is based on the valued ecosystem component (VEC) method. The first step in this method is to choose a key resource or habitat. These resources can be keystone species, which are species that have effects on the structure and function of ecosystems that are disproportionate to its abundance or biomass. These are sometimes large, charismatic species, or economically valued species, but not always. In estuaries, the VEC will likely be biogenic habitats (such as wetlands, seagrass beds, and oyster reefs) that sustain whole communities of other organisms and provide nursery habitats and refuge from predators. The biogenic structure VECs are without doubt the most important ecological units in estuaries in terms of overall ecological services they provide. They may not, however, be considered by themselves as having economic value to many stakeholder groups.

One example of using the VEC approach is in the Caloosahatchie Estuary in Florida. The Caloosahatchie had been subjected to many modifications (channels, canals, and dams), diversions and withdrawals, and this led to decreased sediment transport, biodiversity, and habitat and increased eutrophication and hypoxia in the river. The SFWMD determined a minimum flow to protect VEC habitats would also protect all valued resources. The submerged aquatic vegetation (SAV) was identified as the VEC (Doering et al. 2002). The salinity tolerance to SAVs was measured in laboratory and field studies and used to establish minimum inflow requirements. The MFL was created to maintain salt-tolerant freshwater species in the head of the estuary and prevent mortality of marine species at the mouth of the estuary.

**6.2.3.2 San Francisco Bay, California** - A substantial fraction (up to 50%) of freshwater was diverted from the Sacramento-San Joaquin River system that flows into San Francisco Bay (Kimmerer 2002). The flows were diverted primarily for irrigation and municipal use. The reduced inflow led to decreased abundances of many biotic components, particularly five threatened or endangered fish species. Workshops were convened starting in 1991 to provide scientific input for development of an effective water management strategy. Information was compiled that identified salinity ranges necessary for various natural resources, and relationships between inflow and salinity. Thus, it was recommended that inflow rules could be based on salinity values. A rule was adopted in 1994 to ensure sufficient inflow to locate the 2 ppt isohaline downstream to enhance estuarine resources. This rule, called  $X_2$ , is the distance from the Golden Gate Bridge to the 2 ppt isohaline. Although the estuary system is responding with increased abundances of many species, the salinity standard is a crude tool that could be improved by increased understanding of the underlying mechanisms that control estuarine structure and function (Kimmerer 2002).

**6.2.3.3 South Africa** - Water law was changed dramatically by the 1998 National Water Act, which requires a reserve to satisfy basic human needs and to protect aquatic ecosystems (Adams et al. 2002). The basic human needs reserve is the right of every person to 25 liters (6.6 gallons) of water of adequate quality per day. The ecological reserve is set aside to protect rivers, wetlands, estuaries, and groundwater. All other water use (such as, for agriculture or large volumes for residential or industrial use) must be licensed (or permitted) only after the human and ecological reserves are first met. Thus, there is a need in South Africa for establishment of the ecological reserves for all rivers and estuaries. With this large task, it was necessary to establish a number of methods for determining the reserves, which included:

- The Rapid Method
- The Intermediate Method
- The Comprehensive Method

These three methods have different levels of complexity and accuracy. The selection of an appropriate method depends on the sensitivity of the water resource, scale and degree of impact, proposed water uses, and urgency of determination.

The Rapid Method is a desktop assessment that includes a one-to-two day workshop involving specialists with expertise on the hydrology, physical dynamics, plants, and animals of a particular estuary. A rapid reserve study is based on the generic understanding of estuarine processes and sensitivity to flow alteration.

The Intermediate Method includes limited field surveys, special studies, and a one-to-two day workshop. The duration of the entire study is approximately two months. The study is based on limited, but site-specific data, and knowledge of key abiotic and biotic processes, as well as responses to changes in river inflow.

The Comprehensive Method is similar to that of the Intermediate Method, but the data requirements differ. For example ecological data may be needed for either high or low flow conditions.

For all methods, a seven-step procedure is followed. The procedure has been adapted from the generic procedure established by the Department of Water Affairs and Forestry for the determination of the reserve of all types of water resources. The steps are:

- Step 1. Delineate geographical boundaries.
- Step 2. Establish ecoregional typing (this step applies to water resources other than estuaries).
- Step 3. Assess present state and reference condition.
- Step 4. Determine present ecological status and importance. The present ecological status and importance of an estuary is determined using ecological health and importance indices.
- Step 5. Determine ecological management class.
- Step 6. Set the quantity of the reserve and resource quality objectives (RQO).
- Step 7. Design a resource monitoring program.

An example of how this approach works is illustrated for the Mtata Estuary in South Africa (Adams et al. 2002). For the Mtata River system, storage capacity is 50% of mean runoff, and only 8% of the runoff reaches the sea. Operation of the Mtata Dam for hydroelectric power had reversed the natural flow pattern. The Mtata had high importance scores because it was an ecological reserve, so it has a high inflow requirement. Flows were recommended for May to September to reverse the seasonality of flow back to the natural pattern, promote establishment of a longitudinal salinity gradient, and reduce the sediment load.

**6.2.3.4 Australia** - The Australian National Program is relatively new. There are laws requiring environmental flows to maintain health and biodiversity of rivers and estuaries, but

these are primarily state laws. In 1999, Environment Australia, the Australian federal government Department of the Environment and Heritage, requested proposals to investigate the water required to maintain estuarine processes in the hopes that a standardized methodology could be created. The Water Research Laboratory, University of New South Wales, was chosen to undertake the work and provide a final report (Pierson et al. 2002).

The approach of the recommended Australian National Program is risk-based. The methodology involves an assessment of the risk to the estuarine ecosystem associated with reduced freshwater inflows. This is done by simply reviewing the following check list of major ecological processes affected by freshwater flow to estuaries:

#### ECOLOGICAL PROCESSES CHECKLIST

##### Low Magnitude Inflows (Low-):

- Low-1: Increased hostile water-quality conditions at depth.
- Low-2: Extended durations of elevated salinity in the upper-middle estuary adversely effecting sensitive fauna.
- Low-3: Extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive flora.
- Low-4: Extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota.
- Low-5: Extended durations when flow-induced currents cannot suspend eggs or larvae.
- Low-6: Extended durations when flow-induced currents cannot transport eggs or larvae.
- Low-7: Aggravation of pollution problems.

##### Middle and High Magnitude Inflows (M/H-):

- M/H-1: Diminished frequency that the estuary bed is flushed of fine sediments and organic material (physical-habitat quality reduction).
- M/H-2: Diminished frequency that deep sections of the estuary are flushed of organic material (subsequent water quality reduction).
- M/H-3: Reduced channel-maintenance processes.
- M/H-4: Reduced inputs of nutrients and organic material.

##### Across All Inflow Magnitudes (All-):

- All-1: Altered variability in salinity structure.
- All-2: Dissipated salinity/chemical gradients used for animal navigation and transport.

Upon review of the checklist, there is a two-step methodology that is employed: a Preliminary Evaluation Phase (PEP) and a Detailed Investigative Phase (DIP).

##### Preliminary Evaluation Phase:

- PEP Step 1: Define environmental flow issue.
- PEP Step 2: Assess estuary value.
- PEP Step 3: Assess flow changes.
- PEP Step 4: Assess estuary vulnerability.

Detailed Investigative Phase:

- DIP Step 1: Model project impact on transport, mixing, quality, and geomorphology.
- DIP Step 2: Define environmental flow scenarios.
- DIP Step 3: Use models to assess impacts of scenarios.
- DIP Step 4: Assess biota risk.
- DIP Step 5: License and development approval.
- DIP Step 6: Adaptive management.

### **6.2.3.5 Summary of Concordance Among Approaches**

Setting inflow policy in such a way as to protect estuarine ecosystems encompasses many of the challenges of ecosystem assessment and management in general. As the case studies previously described indicate, there are differences in the details of the technical approaches and scientific methods used everywhere. However, there is also concordance. Except for Texas, where the approach is based predominantly on optimizing commercial harvest, all other areas are protecting the habitats that support valued ecosystem services, such as recreational or commercial fisheries. The approaches range from highly technical to highly value laden, but all are focused on protecting and providing for habitats. In some cases, such as the Caloosahatchie Estuary, Florida, seagrass habitats are explicitly protected. In other cases, salinity rules are used to protect habitat zones for fish and invertebrates. For example, in Tampa, Florida, a “percent of daily flow” approach is used to maintain oligohaline habitat within a certain reach of rivers and streams that feed into Tampa Bay and Charlotte Harbor. In San Francisco Bay, the 2 ppt isohaline is maintained in a certain location during certain times of the year to promote fish recruitment. Finally, in other cases, such as South Africa and Australia, the concept of an ecological reserve is used to explicitly protect habitats and ecosystem services.

The science to support the decision making in all of these examples is varied because the valued ecosystem components providing ecological services vary among individual estuaries. The uniqueness of estuaries, known as the “estuarine signature,” plays an important role, because each estuary is likely to have a unique combination of keystone species and valued ecosystem components. Predicting the ecosystem response to changes in inflow requires that we understand the linkages among these components and the complex interactions between the physical environment and biological structure and function. While this is a general, broad, and complex task, the case studies discussed show that once valued ecosystem components are identified, then more narrow, focused, and specific studies can be performed to detail the flows needed to maintain specific habitats that support the organisms and communities of organisms of concern.

## **7. IMPLEMENTATION STRATEGIES FOR ENVIRONMENTAL FLOWS**

### **7.1 Available Environmental Flow Implementation Strategies**

Turning from the previous section's discussion of the various tools available to assess the environmental water needs of rivers, streams, bays, and estuaries, this section discusses the possible implementation strategies that could be used to achieve the desired flows, once the target amounts and allocation pattern have been established.

Implementation strategies for achieving desired levels of environmental flows can be generally grouped into two categories: regulatory and market-based. An overview of these two categories and the types of strategies that fall within them are described in the following sections. These strategies are drawn from the literature and from what is being practiced in Texas today. They are intended to provide a relatively broad representation of available options rather than serve as recommendations.

It is important to observe at the outset that the starting point can matter a great deal in shaping the implementation strategy or strategies for providing for environmental flows. Broadly stated, two starting points are possible, depending on whether or not sufficient unappropriated water is available to meet environmental flow targets. If insufficient unappropriated water exists, one of the main objectives of the implementation strategy is to "recover" water for environmental flows from existing permits (water rights). In this case, many of the regulatory approaches described below may prove to be politically difficult to implement, and could raise the possibility of legal challenges. Market-based strategies, by which existing water right holders voluntarily enter into transactions by which their rights are converted or modified to provide for environmental flows, are likely to offer the best means to recover the necessary water to satisfy environmental flow requirements. In the case where sufficient unappropriated water exists, regulatory approaches that allocate the water to fulfill environmental flow needs may prove to be efficacious strategies, with market-based strategies serving as a mechanism for adapting to the natural dynamics and inherent uncertainties associated with environmental flows. In general, it certainly is more difficult/costly to recover the water to meet environmental flow needs from existing permits than it is to allocate or reserve water for environmental flows directly, if that option is available.

#### **7.1.1 Regulatory Environmental Flow Strategies<sup>13</sup>**

Regulatory strategies are those that would utilize the legal and regulatory authority of the state to directly allocate water for environmental purposes, stipulating that specified quantities of water be passed downstream before any water can be diverted or impounded, thereby reserving the bypassed flows for environmental purposes, for a specified stretch of a river or stream. A broad spectrum of strategies exists. Some of the most common approaches are described briefly in the following sections.

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<sup>13</sup> This section draws from a variety of sources that include Seibert et al. (2000), National Wildlife Federation (unpublished), and Instream Flow Council (2002).

### **7.1.1.1 Environmental Flow Reserves**

An authorized state entity would reserve or “set aside” surface water flows solely to meet the target environmental flow requirements for a particular watershed or stream reach. No permits for consumptive use (diversions or impoundments) could be issued by the state that would reduce these reserved flows. In Texas, the state currently does not have such authority.

**Pros** – The state entity could act directly on behalf of the public, in the interest of the public good. With proper authority, the implementation process is relatively simple.

**Cons** – The use of the reserved water would have a priority date that is “junior” to existing water rights permits, thus potentially limiting its availability during low-flow periods when supplies are diminished. To be effective, there must be sufficient unappropriated water available to provide for the reserved flows.

### **7.1.1.2 Environmental Flow Permits**

A permit (water right) for a given quantity of environmental flows would be issued to a governmental or non-governmental entity or private individual through the water rights permitting application process. The total amount available for environmental flows permits in a particular watershed or stream reach would be set at the target level for that particular watershed or stream reach, and permits for environmental flows would not be issued in excess of that amount.

**Pros** – An enforceable water right for environmental flows would be created, with all of the authority and protection afforded other water rights.

**Cons** – Any new permit authorizing a certain level of environmental flows would have a priority date that is “junior” to existing water rights permits, thus potentially limiting the availability of water to sustain the environmental flows during low-flow periods when supplies are diminished. To be effective, there must be sufficient unappropriated water available to allocate to the environmental flow permit. Acquisition of an environmental flow permit also would require an applicant willing to shepherd the permit through the permitting process and pay the associated costs.

### **7.1.1.3 Environmental Flow Conditions Attached to New Water Rights Permits**

New water rights permits for non-environmental uses would include conditions to protect environmental flows, stipulating that specified quantities of streamflow be passed downstream before any water can be diverted or impounded, thereby reserving the bypassed flows for environmental purposes, for a specified stretch of river or stream. The nature and scope of these conditions would be established by a state entity using all available information regarding environmental flow targets for the subject watershed or stream reach. Also, the conditions would be subject to scrutiny and review by affected parties, and possibly to revision, through the permitting process. This is basically the strategy that has been used for providing for environmental flows in Texas. (See detailed description in Section 7.3)



**Pros** – The state entity can act directly, in the interest of the public good. It is relatively easy to implement (and in the case of Texas, is already in place). This approach has been done and accepted, the mechanism for implementing this approach is in place within the State, and it is an established practice that can assure adequate environmental flows for limited segments of rivers and streams and for the bays and estuaries.

**Cons** – Without proper state coordination and direction, adding environmental flow conditions to new permits can result in an ad hoc approach that makes it difficult to sufficiently and comprehensively achieve environmental flow targets. This strategy cannot address existing water rights that do not have environmental flow conditions, and there must be sufficient unappropriated water available to ensure that the environmental flow targets can be satisfied during low-flow periods when supplies are diminished. Unless conditions explicitly incorporate mechanisms for later modification, adjusting the quantity of environmental flows provided for in the condition could be difficult, if not impossible.

#### **7.1.1.4 Water Taxes**

A portion of the water involved in market transfers would be returned to the environment in the form of environmental flows. Such water taxes for environmental flows could be a fixed percentage of the transfer amount or a sliding-scale fixed amount as a function of the transfer amount. The resulting environmental flow amount would then be converted to either an environmental flow reserve or an environmental flow permit subject to administration by the state.

**Pros** – This strategy could be effectively implemented, provided that the necessary authority was provided to the administering state agency. The resulting quantities of water available for environmental flows would be authorized and protected to the same extent as the originating water rights.

**Cons** – This strategy could discourage beneficial and necessary water transfers; it would provide and protect environmental flows within a watershed or stream segment only in the immediate vicinity of the originating water rights and downstream only as far as the next senior water right; and its implementation would likely be controversial among stakeholders.

#### **7.1.1.5 Reservation of Return Flows**

Instead of allowing full reuse of all historically discharged municipal return flows when wastewater reuse applications are being considered, the state would reserve a specified percentage, e.g., 10% to 30%, of the return flows for environmental purposes. The resulting environmental flow amount would then be converted to either an environmental flow reserve or an environmental flow permit subject to administration by the state.

**Pros** – This strategy would be relatively simple to administer, provided the necessary authority was provided to the administering state agency. If applied to both direct (flange-to-flange) and indirect (bed and banks) reuse projects, there would be trade-off between less water available for direct reuse projects and reduced permitting complexities for indirect reuse projects. The resulting quantities of return flows available for environmental flows could be authorized and protected to the same extent as the originating water rights.

**Cons** – Return flows originating from groundwater or interbasin transfers would require special consideration; benefits of any environmental flows resulting from return flows would be realized and protected only in the immediate vicinity of the reuse project and downstream only as far as the next senior water right; and implementation of this strategy could be controversial among stakeholders. The use of return flows to create environmental flows (either as a permit or reserve) could have a priority date that is “junior” to existing water rights permits, thus potentially limiting its availability during low-flow periods when supplies are diminished.

#### **7.1.1.6 Superceding Public Interest**

Based on the public trust doctrine and the “usufructuary” nature of water rights permits in Texas, the state could assert superceding interest on existing permits (water rights) for the purpose of providing environmental flows for the greater public good. Possible applications of this approach range from the cancellation of unused rights and their conversion into environmental flow reserves or permits (possible under existing water code); placing environmental flow conditions (reservations) on existing water rights; or, in the most extreme case, “condemning” existing water rights permits for public use as environmental flows.

**Pros** – This strategy can address sharing of the burden of providing for environmental flows among all existing water rights, even senior water rights that currently have no duty to pass or reserve flows for environmental purposes, and it can provide for environmental flows in over-appropriated basins where the issuance of new permits is not likely.

**Cons** – This strategy would be politically unpopular to implement and extremely controversial among stakeholders, and it is likely to be perceived as interfering with property rights (i.e., unconstitutional), with very high potential for extended litigation.

#### **7.1.2 Market-Based Environmental Flow Strategies**

Like most other western states, surface water supplies in much of Texas are fully appropriated. As noted above, when starting from a position of over-appropriation, achieving target environmental flows will likely require reallocation of existing supplies. Market-based approaches have become important mechanisms that can create unique and important opportunities for voluntary water reallocation, helping to balance competing water demands, including environmental flows.

##### **7.1.2.1 Water Markets**

The term “water market” refers to the exchanges of water rights (permits) by willing sellers and willing buyers in a given region, or for a particular water body. It is important to recognize that the geographic extent of markets for surface water is dependent on the size of the watershed (excepting interbasin transfers). States that contain multiple watersheds would consequently require multiple water markets that allow for exchange of permits within those watersheds. Water markets can take a number of forms, and exchanges can be made for both water rights themselves (permanent), and leases of agreed-upon quantities of water but not the rights (temporary). In the specific case of environmental flows, exchanges may also take the form of a donation, if water regulation makes that option available. Water markets exist in nearly every

state in the western United States, and are being considered in eastern states such as Florida, North Carolina, and New York.

As with any water management tool, water markets face a number of potential problems and complications. Restrictions on certain types of trades are common, particularly in the case of irrigation organizations, such as cooperatives or irrigation districts. Restrictions may include those on trades that involve changes of use, transfers of ownership outside of the organization, and trades to locations outside the river basin (Wilkinson 1986). In addition, water markets are particularly prone to third-party effects. Transfers of water rights may alter the spatial and temporal pattern of diversions and return flows, affecting large numbers of right holders not directly involved in the transaction (i.e. third parties). In some irrigation organizations, trades may be blocked by the protest of a third party who would be adversely affected (Colby 1990b). Other problems that may impair the performance of water markets include few buyers and sellers (i.e. thin markets), high transaction costs, imperfect information, and the public good aspects of instream uses for water (Brajer and Martin 1990; Colby 1990a, b, and 1989a; Randall 1983). Bauer (1998, 2004) analyzes the experiences of Chile, where the government has been among the most active in the world in establishing water markets, and finds that virtually all of these problems have affected Chilean water markets.

Nonetheless, participation in water markets can be an effective approach for acquiring water rights to meet environmental flows needs. For markets to be used to provide water for environmental flows, environmental flows—or more generally, non-consumptive uses—must be recognized as legitimate and legal. Such “instream flow” rights are recognized in some form in nearly every western state. However, individual participation in water markets for the purpose of acquiring rights for environmental flows is rare, and may be precluded under existing water regulation. Instead, transactions to acquire environmental flows typically involve either state entities or, if the water code permits, private, non-profit organizations (see the following discussion of water trusts) established to represent the demand for environmental flows in the market. Environmental and instream flow demands are a growing part of nearly every western state water market. With the exception of Wyoming, environmental water sales have occurred in every western state. This market sector has increased steadily since 1990, when less than \$500,000 was spent on water purchases. In comparison, more than \$11 million dollars was expended from 1990 to 1997 on purchases of water to improve habitat conditions for fish and wildlife (Landry, 1998). Expenditures for environmental water acquisitions throughout the western United States are currently estimated at \$20 million per year (Landry 2003).

**Pros** – This approach provides a voluntary mechanism by which existing water rights for human uses can be reallocated for use as environmental flows. Because it is an “ownership rights” based approach, it avoids many of the potential problems associated with regulatory approaches previously described. It also provides the opportunity to acquire senior water rights for use as environmental flows.

**Cons** – The water-market approach requires that entities seeking to acquire water rights for environmental flows have the financial resources to participate in the market sufficiently to obtain the target level of environmental flows. If left to decentralized efforts and financing from multiple participants, it is unlikely that sufficient water rights will be acquired to meet environmental flows targets. Decentralized efforts may also lead to high “transaction costs,” which include costs associated with locating trading partners, developing contracts, and working

out trading procedures. Because widespread use of water markets in Texas would be a new approach, potential participants may have limited experience with banking and may not fully understand how the bank functions. Potential participants may hold back during the initial trading periods to observe and gain market information and then enter once the market is more established. Water trusts (see following section) represent a way to address many of these issues.

### 7.1.2.2 Water Trusts

For the purposes of this report, an environmental flows “water trust” is a formally organized and recognized entity that has been established to hold and manage water rights specifically to provide environmental flows. A water trust can exist as either an entity of the state or as a private non-profit organization. Oregon and Washington have statutes that specifically allow private entities to acquire water rights for instream use. The new instream water rights are held in trust with the state. However, the organizations maintain a fiduciary responsibility to instream rights. As a result, private entities have legal authority to monitor and enforce the instream rights. Though it may be too early to tell, it appears that states such as Oregon, Washington, and Montana that allow for some form of private ownership or holdership have tended to see environmental flows evolve more quickly. Table 7-1 provides a summary of private conservation organizations active in water throughout the western United States. Assuming that sufficient funding is available to them, water trusts can participate in water markets to acquire rights to be used for environmental flows. Importantly, water trusts can also acquire water rights through donation. It is important note that, although Texas has established a state entity called the “Texas Water Trust,” it serves a slightly different function as simply the holder of water rights that can be placed in the Water Trust—either for a limited period of time or permanently—for use in meeting environmental flow needs (see more detailed discussion of the Texas Water Trust that follows).

**TABLE 7-1 PRIVATE NON PROFIT ENVIRONMENTAL WATER MARKET ORGANIZATIONS**

Organization	State	Focus
Colorado Water Trust	Colorado	State-wide organization
Deschutes Water Exchange	Oregon	Deschutes Basin
Klamath Basin Rangeland Trust	Oregon	Klamath Basin
Great Basin Land & Water	Nevada	Truckee Carson Basin
Montana Water Trust	Montana	State-wide organization
Montana Trout Unlimited	Montana	State-wide organization
Oregon Water Trust	Oregon	State-wide organization
Washington Water Trust	Washington	State-wide organization
Walla Walla Watershed Alliance	Washington	Walla Walla Basin

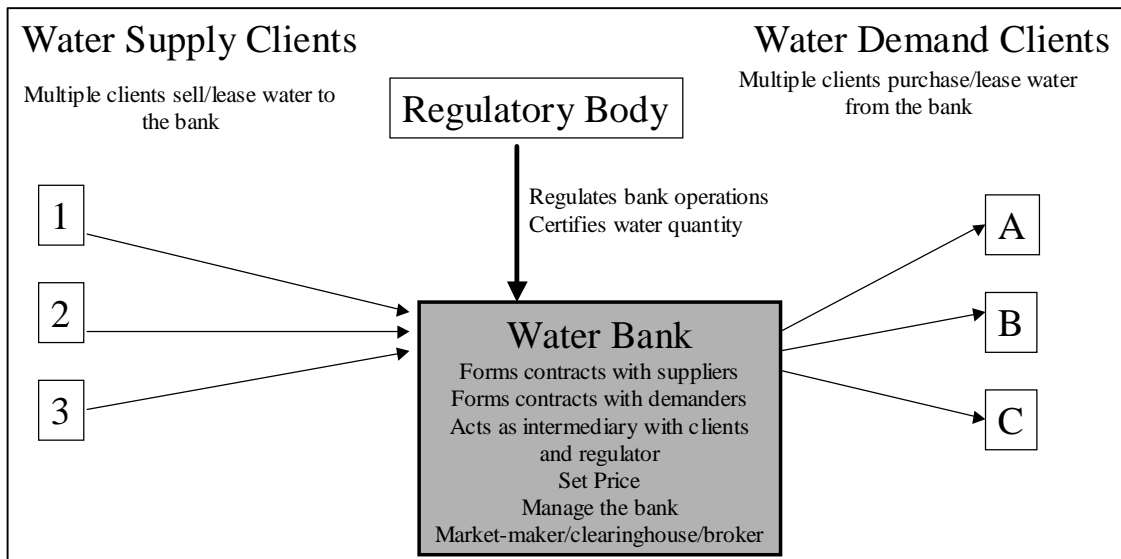
**Pros** – Provides legal authority for a single entity to participate in the water market with the objective of acquiring water rights for providing environmental flows. Offers the ability to coordinate transactions and develop institutional skills and knowledge so that transaction costs

can be reduced. If provided with a mandate to achieve target environmental flows, the water trust can coordinate transactions so that the target can be effectively achieved.

**Cons** – Requires adequate funding (public or private) for buyers to be able to sufficiently participate in the market to acquire environmental flows.

### 7.1.2.3 Water Banks

The term “water banking” is used to refer to a variety of institutional and water management practices. For this analysis, water banks are broadly defined as an institutional mechanism that facilitates the legal transfer and market exchange of various types of surface, groundwater, and storage entitlements. Water banks often allow “unused” water to be “stored” for future use, while in the interim this banked water is available for “lease” by others. In effect, the bank acts as an intermediary, or broker, where it brings together buyers and sellers (Figure 7-1). The banking administrator can provide a host of administrative and technical functions that serve to lower transaction costs, such as those associated with locating trading partners, developing contracts, and working out trading procedures.



**FIGURE 7-1 WATER BANK CONCEPTUAL MODEL**

Operating water banks have developed variations on the basic model in Figure 7-1 that suit their budgets, regulatory environment, and individual bank goals. In general, banks with larger budgets and outside funding (e.g. mill levy as is the case for the California Drought Bank) have the financial backing to take a position in the market by buying and selling water. In contrast, banks that rely on administrative fees to cover their operating costs tend to act as brokers and try to clear the market by matching offers from buyers and sellers. The level of bank involvement in market trades can differ greatly, depending on the type of market, pricing rules, and contract structures put in place.

Water banks are often designed around a specific source or type of water entitlement, and can be classified into three major categories that describe sources that drive the design and structure of banks. Due to the wide range of legal and institutional structures that exist, some banks could be classified in multiple categories.

- Institutional Banking – An institutional bank provides a legal mechanism for exchanging water rights and other various forms of entitlements. These banks are often called paper exchanges in reference to the transfer of legal documents that represent a specific water quantity.
- Surface Storage Banking – These are typically formed around a reservoir or series of storage facilities where storage allotments can be banked and exchanged. By definition, the exchange of water is backed by physically stored water. Unlike institutional banks, surface storage banks provide greater reliability in supply.
- Groundwater Banking – Groundwater banking is a recent development in water-banking concepts. Groundwater banking programs provide a mechanism for exchanging credits or entitlements for water withdrawals within an underlying aquifer. Several programs have been developed to address conjunctive use and extensive surface water withdrawals.

**Pros** – Provides institutional expertise and services that can significantly reduce transaction costs.

**Cons** – Requires adequate funding (public or private) for buyers to be able to sufficiently participate in the market to acquire environmental flows. While the number of water banks in the last 10 years has increased, trading activity measured both in the number of transactions and amount of water has not increased significantly. The limited market activity is partly explained by the following:

- Restrictions are placed on the number and type of participants.
- Many water banking programs around the United States are relatively new. As a consequence, potential participants have limited experience with banking and often do not fully understand how the bank functions. Potential participants will often hold back during the initial trading periods to observe and gain market information and then enter once the market is more established.

#### **7.1.2.4 Water Leasing Programs**

It is important to recognize that water banks, as defined here, are distinct from leasing programs. As described above, a bank involves the exchange of water entitlements through the interaction of multiple buyers and sellers. In contrast, a leasing program is usually designed for a single buyer, typically either a state entity or a private water trust, to solicit and temporarily obtain water from multiple sellers for a specific use. So called “lease banks” are often used to obtain water for environmental purposes. Lease banks tend to be more restrictive and do not provide a mechanism for water to be acquired by third parties.

**Pros** – Leasing programs provide legal authority for a single entity to participate in the water market, with the objective of acquiring water rights for use as environmental flows. They offer the ability to coordinate transactions, and develop institutional skills and knowledge so that

transaction costs can be reduced. If provided with a mandate to achieve target environmental flows, the water trust can coordinate transactions so that the target can be effectively achieved.

**Cons** – This approach requires adequate funding (public or private buyers) to be able to sufficiently participate in the market to acquire environmental flows.

#### **7.1.2.5 Other Considerations Regarding Market-Based Strategies**

Several states have adopted policies and created programs that have resulted in active and growing environmental markets. Policy and funding measures that could be considered in Texas to realize the full potential of environmental water markets include:

- State funding and resources made available to acquire water rights for deposit in the Texas Water Trust.
- Establishment of state tax incentives to encourage more donations of water rights to the Texas Water Trust.
- Creation of a private non-profit entity, dedicated to acquiring water rights for instream use.
- Provisions for private ownership of instream water rights.
- Policies, such as a mitigation strategy, which provide incentives for increased private-sector funding for instream water right acquisitions.

#### **7.1.3 Combination Environmental Flow Strategies**

Regulation and market mechanisms can be combined in a variety of ways that seek to take advantage of the “pros” of the particular strategies in question, while offsetting or mitigating to the extent possible, their respective “cons.” Thus, combination strategies, if carefully crafted, can provide potential advantages over “single strategy” approaches. For example, a reserve or set-aside approach could be used when adequate unappropriated flows exist to meet target environmental flows. If insufficient unappropriated flows exist, a combination of reserve and market approaches could be used to initially set aside whatever flow amount is possible, while the remainder of the target environmental flows is acquired through market transactions. As another example of a combined approach, the initial allocation for environmental flows could take the form of a reserve established and set aside directly by the state. To deal with fluctuations in precipitation, spot market transfers (transfers of water rather than the water right itself) could then occur in response to low- and high-precipitation periods, by selling a prescribed amount of water during dry spells, and then using these funds to purchase water during wet periods. The purchased water then could be used to achieve high-flow pulses or overbanking as part of an overall environmental flow program.

#### **7.2 Other Considerations Regarding Environmental Flow Strategies**

Implementation strategies for achieving environmental flows in a watershed or a stream segment should explicitly acknowledge and seek to incorporate mechanisms that account for: (1) cycles, fluctuations, and the dynamic aspects of the water source and the ecosystem; and (2) uncertainty and risk, particularly drought and exceptionally low-flow conditions. These mechanisms should

be designed to avoid extreme risks and to incorporate adaptive flexibility into the implementation process.

### **7.2.1 Dealing with Changing Conditions**

The complex, interdependent, and non-linear interactions among the various ecosystem components exist within the context of highly variable rainfall and streamflows under natural conditions. The relationship of water's role in ecosystem functions is the subject of continuing scientific investigation and is yet to be fully understood and described. In general, the variability of environmental flows can be viewed as an essential component of the "health" of the ecosystem in terms of maintaining the integrity of ecosystem structure and function (see e.g., Poff, et al. 1997). Thus, beyond a single constant flow value, inter- and intra-annual variations of flows are widely recognized elements that are of critical importance to ecosystem sustenance.

However, the requirements of both riverine and estuarine ecosystems for significant variations and fluctuations in environmental flows are incongruent with human efforts to: (1) remove variation from the available water supply (e.g., reservoir construction); and (2) institutionalize the regularity of use by means of water permits (water rights) that are couched in static terms of a single annual amount, in perpetuity. If a water right is to be assigned to the ecosystem as a means to implement environmental flows, the challenge is how to incorporate the necessary inter- and intra-annual variations within the existing institutional (i.e., legal and regulatory) framework regarding water rights.

Market-based approaches to re-allocation of available water may, if carefully designed, provide a means for achieving some degree of dynamic flexibility within the existing institutional framework that is consistent with the variability needs of the ecosystem. The effectiveness of this approach is, of course, dependent on the existence of an entity with the authority to operate in the market in pursuit of achieving environmental flow targets and with the funding to be able to participate in the necessary exchanges.

### **7.2.2 Dealing with Risk and Uncertainty**

The inherent uncertainties associated with establishing environmental flow targets include: (1) lack of basic understanding regarding some water-ecosystem interactions and relationships; (2) lack of data at appropriate spatial and temporal scales; (3) complex natural processes and non-linearities; and (4) the extreme variations and apparent randomness of weather events and other natural phenomenon. An additional set of uncertainties may pertain to the performance of the chosen strategy by which the environmental flow targets are to be achieved. These uncertainties lead to the risk that adequate environmental flows may not be achieved, with negative consequences to the ecosystem. The elements of uncertainty and risk can become an especially important component of the policy-making process in cases in which: (1) the potential damage of the activity could be large; (2) significant time and/or distance separates the activity and its impact; (3) an incomplete knowledge exists regarding the nature and severity of the impact; (4) sufficient monitoring and enforcement are unlikely; and (5) the lack of a suitable method for determining the amount of water required for environmental purposes creates uncertainty.

Uncertainties and risks appear in a wide variety of environmental issues. For example, in water quality risk management, the precautionary principle is often used to ensure human health and



safety. The precautionary approach is based on the idea that when facing uncertainty in a risk analysis, the regulatory level should be set at the lowest concentration of a pollutant that is thought to pose a risk to health. After further research, regulatory levels can always be relaxed (increased) if higher levels are shown not to pose health risks, but the public health has been provided protection during the period of scientific uncertainty. If the precautionary principle were used in water management decisions without regard for other important needs for water, then higher levels would be set for environmental flows until lower levels were proved not to injure ecological health. Conversely, the commitment of higher flows for environmental purposes often is viewed as an irreversible process, with yet to be identified other needs for water—including water for human consumption and public health—at risk as well. Certainly, the risks and uncertainties represent a significant challenge to decision makers and water managers when considering the provision of environmental flows.

In some cases, insurance markets arise in response to risk (e.g., flood insurance, drought insurance, construction bonds), which serve to quantify the risk in dollar terms, and “internalize” the risk as a cost, bringing it squarely into the decision-making process. However, in many other instances and for a variety of reasons, private insurance markets do not emerge, resulting in a burden of risk that may be entirely omitted from the decision-making process. In these cases, which include the impacts of changes to environmental flows, other insurance mechanisms can be devised to account for the possible damage.

To address this issue, strategies designed to achieve the desired environmental flows can incorporate mechanisms that account for the following: (1) the uncertainty inherent in the scientific understanding of environmental flows and the impacts of their alteration; (2) fluctuations of weather and other natural processes; and (3) the uncertainties regarding the performance of the implementation approach itself. Perhaps more importantly, these strategies could explicitly account for the risk associated with “getting it wrong,” thus incorporating adequate “insurance” mechanisms into decision making and the allocation process regarding environmental flows.

For example, once the target environmental flow pattern is determined, an additional buffer or reserve amount dedicated to serving as environmental-flow “insurance” could be established. This reserve would provide a degree of insurance against: (1) the risk that the target environmental flow pattern underestimates the needs of the ecosystem, and (2) the risk that the implementation strategy under-performs in achieving the desired environmental flows pattern. It thus could serve as part of an adaptive management strategy (see following section) that allows “room for maneuvering” in the face of existing uncertainties, while reducing the risk of erring on the side of insufficient environmental flows. Of course, all of this assumes that an acceptable balance can be achieved among all water interests for satisfying water demands, including meeting human needs, as well as providing adequate environmental flows.

### **7.2.3 Adaptive Management**

The various uncertainties associated with environmental flows point toward an implementation strategy that operationalizes a degree of responsive flexibility. This flexibility allows for adjustments over time, as more information and understanding is obtained regarding the relationship of environmental flows to the ecosystem and the performance of the implementation strategy. Such adaptive capacity can be achieved through an iterative process that involves: (1)

choosing an environmental flow target and the strategy by which the target is to be pursued, even if significant uncertainty exists; (2) monitoring the impact of the target flows on the ecosystem, as well as the effectiveness of the strategy in achieving the target; (3) learning from the new information gathered; and (4) implementing changes, adjustments, and revisions to the environmental flow target, the implementation strategy, or both, based on the new information gathered. This iterative process is often referred to as “adaptive management” (see Lee 1993; Instream Flow Council 2002) and has been a suggested approach to a wide variety of applications in which decisions must be made and actions taken within the context of significant uncertainty.

Again, if carefully designed, and combined with an adequate insurance mechanism, both regulatory and market-based approaches for implementing environmental flow targets for new appropriations and for re-allocation of existing water supplies to environmental purposes can provide a means of incorporating adaptive flexibility into the environmental flows process. This would allow the environmental flow targets to be adjusted upward or downward as determined by the science, as more information and improved understanding are obtained. It is important to recognize, however, that simply agreeing to utilize an adaptive management approach does not ensure that appropriate environmental flow targets will be ultimately achieved. The complexities and conflicts associated with satisfying competing demands for water still have to be dealt with, and compromises among the different water users or uses often are necessary and unavoidable. What is important is to apply the best science available to arrive at the best estimate of environmental flow needs for a particular situation, and then to attempt to implement the strategies necessary to achieve these environmental flow targets while balancing all other interests and water demands. One way to accommodate the uncertainties inherent in the environmental flow targets through the adaptive management process is to establish reasonable and scientifically determined ranges on how much the targets can be changed (increased) in response to improved science or on how much the changes in the targets can affect (decrease) the dependable water supply of an associated water development project. Such limits would provide some degree of certainty and risk protection to water developers, while at the same time, providing for an initial base flow level, and an additional reserved amount, of environmental flow protection. These limits, however, have the potential to result in environmental flow targets that do not fully achieve desired soundness of the ecological environment. The key is to assure that rigorous and defensible science is applied on a case-by-case basis in order to derive the best estimates possible for the required environmental flow targets and the corresponding limits on changes to those targets.

## 8. SUMMARY OF FINDINGS

### 8.1 General Overview

The question is not whether environmental flows are important and should be protected, but rather, how, when, and where, and in what quantities should flows be reserved for environmental purposes in the state's rivers and streams and its bays and estuaries. The State of Texas has investigated environmental flow issues for several decades. Scientific methods, protocols, and understanding regarding environmental flows have significantly progressed through the course of the previous 40 years and continue to evolve and improve. Due to the complexities of environmental flow issues and continuing advances in scientific understanding, additional work is needed. While the State of Texas has pioneered tools to address freshwater inflow needs for bays and estuaries, there are limitations to these tools in light of both scientific and public policy evolution. To fully address bay and estuary environmental flow issues, the foundation of work accomplished by the state should be improved. While the Texas Instream Flow Studies program appears to encompass a comprehensive and scientific approach for establishing environmental flow needs for rivers and streams across the state, more extensive review and examination of the details of the program, which may not be fully developed until the program is underway, are needed to ensure an effective tool for evaluating riverine environmental flow conditions.

Legislative directive within Texas on environmental flows has also changed over recent decades. This change in directive reflects the evolving state of understanding of the environmental flow problem. In 1985, the Legislature directed the state water agencies to determine sufficient beneficial freshwater inflows "... 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." This is essentially a macro-level approach to the question of sufficient freshwater inflows. The apparent interpretation of this language by the state resource agencies was that it meant to determine inflows that could support key (i.e., a subset of) sport and commercial fish and shellfish species.

By year 2001, within Senate Bill 2, the Legislature directed the state water agencies to "... conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state's rivers and streams necessary to support a sound ecological environment." Addressing a sound ecological environment requires study of the total (complete) aquatic ecosystem and, from a scientific perspective, emphasizes preservation of habitat for desired species as opposed to the state's earlier focus on species abundance. Senate Bill 1639 in the 78<sup>th</sup> Legislative Session continued the Senate Bill 2 theme, identifying "biological soundness" as a goal for the state's waters. Biological soundness should be distinguished from soundness of the hydrologic, geomorphologic, or any of the other natural sciences as it relates to streamflows.

Today, the State of Texas is at a crossroads, where the science of evaluating and determining environmental flows is being comprehensively assessed as a contribution to the state's effort to develop effective environmental flow policy. Based on review of this subject by the Science Advisory Committee, the following observations are offered.

1. A “one-size-fits-all” answer is not correct within Texas. The current climatologic, hydrologic, and aquatic environments vary drastically across the state, meaning some parts are more fragile or more susceptible to harm with small changes in environmental flows. This fact must be acknowledged and considered with respect to scientific study, water management strategy implementation, and regulatory permitting. In the future as in the past, basin and subbasin scientific studies must be devised and then implemented. It is important that in the future the development of environmental flows pursuant to permitting must recognize the essential qualities of specific locations.
2. *Future scientific studies need to focus in more detail on the specific relationship between sound ecological environment and streamflows.* Scientific analysis objectives within the state should be directed toward defining what constitutes a sound ecological environment and the interconnections between streamflows and the biology and hydrography of riverine and estuarine systems. From such scientifically established relations are determined the environmental flows necessary to maintain a sound ecological environment.
3. *Completion of the Texas Instream Flow Studies program and improvement of the bays and estuaries freshwater inflow studies are essential.* Each of these efforts is critical for the state to achieve its goals relative to environmental flows.
4. *Participation by stakeholders and water interests in the environmental flow program and rigorous scientific review are of paramount importance to achieving acceptable environmental flows.* Only through a transparent process can appropriate scientific methods be employed and scientific results be formulated.
5. *For evaluating environmental flows for rivers and streams, statistical desk-top methods and associated technical analyses must be enhanced to facilitate regulatory permitting actions until such time as the Texas Instream Flow Studies program is completed.* The current Lyons and CPC methods appear to have limitations as currently applied. A body of professionals should be charged with review of currently available assessment tools and the development of alternative methodologies for evaluating riverine systems. These enhanced methodologies may also be necessary in the long term as the Texas Instream Flow Studies program may be too resource intensive for every situation.
6. *The TWDB’s State Methodology and the TPWD’s “verification” process used to develop freshwater inflow recommendations for the state’s bays and estuaries exhibit scientific shortcomings that must be addressed.* The measure of abundance used is commercial harvest (except for the recent Sabine Lake recommendations), which has a poor relation to ecological soundness; the various statistical methods employed are questionable, including regression forms and definition of independent variables; the resulting “optimum” inflow regime is mainly determined by constraints, which are arbitrarily specified; and the optimum solution bears no relation to actual harvests, nor do the optimum patterns of inflow occur in the natural hydrology. The TPWD’s verification process is actually a comparative analysis between the *minQ* and *maxH* solutions, and favors the optimal solution with the greater inflow to the bay. One of

the most important questions relating to management of inflows to the Texas bays is unanswered by the State Methodology and the TPWD verification analysis, namely under drought conditions what inflows must a bay receive to maintain its ecosystem over the long term.

7. *Adaptive management and precautionary principle methods must be incorporated into the scientific study, management strategy implementation, and regulatory permitting phases of future environmental flow activities.* History proves that the present science of environmental flows is complex, inexact, and subject to varying levels of uncertainty. These shortcomings identify a need for an overall environmental flow strategy that facilitates change as future information becomes available. Any future adaptive management approach must consider the need for assuring dependable water supplies for human use and must provide reasonable and scientifically-determined boundaries that limit supply risk while also recognizing scientific uncertainty and erring on the side of caution if the risks of environmental damage are high.
8. *There are both regulatory strategies and market-based strategies that can be used to provide for environmental flows.* The state currently has mechanisms for both, but it is not evident that these approaches, as currently structured, are adequate to comprehensively ensure target environmental flows. Further evaluation of existing and alternative regulatory and market-based approaches should be explored to provide for a more comprehensive and effective environmental flow program that addresses both riverine and estuarine needs for the state.

The need for defensible science and acceptable answers relative to the state's environmental flow programs is of paramount importance. While progress has been made, there is work to be done. The Texas Instream Flow Studies program provides the framework for developing scientifically-based basin- and subbasin-specific estimates of environmental flows for rivers and streams across the state, and it needs to proceed following the National Academy of Sciences (NAS) review. Likewise, the data and methodologies being employed for establishing freshwater inflow requirements for the state's bays and estuaries and the results generated need to be thoroughly examined and modified as necessary to provide more scientifically-based answers that are responsive to actual needs of the coastal systems. Less consideration should be given to determining "optimal" levels of freshwater inflow to the bays and estuaries, and more emphasis should be placed on addressing the extreme hydrological events that periodically cause major stresses on the ecological integrity of these systems, notably low-flow and drought conditions.

## **8.2 Key Points Related to SAC Charges**

**8.2.1 Charge 1. Provide a description of the current hydrologic conditions, streamflow patterns across the State in major river basins, and freshwater inflow patterns for major bay and estuary systems along the coast, relative to historical and existing environmental flows.**

### **8.2.1.1 Hydrology of Texas**

Climatology of rainfall, hence streamflow, in Texas is highly variable in both space and time. Almost all rainfall in Texas is derived from thunderstorms. The resulting streamflow is

characterized by high spikes, rising and declining on a time scale of days, superposed on a much lower and less variable baseflow. Springflows provide baseflow in many basins, with the largest springs in the Colorado, Guadalupe, San Antonio, Nueces, and Rio Grande Basins. Reductions in these springflows caused by groundwater withdrawals often diminish baseflow to levels that can impact water available for environmental purposes.

On a time scale of months, there is substantial seasonal variation in streamflow across the state, though the season of high flow depends upon location in the state. Most of Texas has bimodal seasonal streamflows with maxima in spring and fall. On a time scale of years to decades, large-scale shifts in global atmospheric patterns produce recurring drought conditions, which are the most stressed periods in terms of both water supply for humans and flows needed for environmental purposes in the state's watercourses. The need for reliable water supplies during droughts has led to the state's extensive system of reservoirs and water delivery systems.

As part of the state's water availability modeling, a synthetic time history of "naturalized flows" has been developed for each basin in the state in which the effects of water-supply structures and diversions on the historical data record have been estimated and removed. These "naturalized flows" provide a capability for measuring human impacts on a stream or river, but do not take into account all human influences, such as modifications to watersheds that have occurred over time due to deforestation, urbanization, etc. Analysis of flows under full water rights utilization is not reflective of actual conditions as it assumes all water rights are fully utilized all at the same time, year after year, instead of the condition being manifested over time.

- In general, streamflows and freshwater inflows under current conditions are less than those under naturalized conditions, because the former reflects the influence of water supply structures (reservoirs) and diversions. In some cases, return flows and reservoir releases can result in current-conditions flows that are greater than naturalized flows.
- Bay and estuary inflows under conditions corresponding to the full utilization of existing water rights indicate significantly greater reductions from naturalized inflows compared to current-conditions inflows because, in the later case, much of the appropriated water has not yet been used.
- In general, water use and water supply structures, as represented by current conditions, have altered both the quantity and timing of streamflow, as compared to naturalized conditions, and these alterations are greater in some basins than others.

### **8.2.1.2 State Surface Water Regulation**

Water rights in all river basins in Texas except the Rio Grande are based on the prior appropriation doctrine whereby appropriators are subject to curtailment of their available water supplies during times of water shortage based on the priority dates of their respective water rights. Under this system, water rights with older priority dates, regardless of their type of use, are entitled to use their full authorized amount of water first in priority order, with junior water rights subject to curtailment as available supplies diminish. Water rights on the Rio Grande downstream of Amistad Reservoir are subject to a class-based system adjudicated by the courts whereby, during times of shortage, domestic, municipal, and industrial water rights are entitled to use Rio Grande water before irrigation, mining, and other water rights.

Since 1985, the TCEQ and its predecessor agencies have been charged with assessing and considering the impacts of new appropriations of surface water (and certain amendments of existing appropriations) on instream uses, fish and wildlife habitat, water quality, and bay and estuary needs. In the regular granting of permits for the use of state waters, Senate Bill 1639, which was enacted during the 78<sup>th</sup> Legislative Session (2003), expressly requires the TCEQ, while balancing all other interests, to include in permits provisions considered necessary to maintain existing instream uses and water quality of the impacted stream. The TCEQ may grant an application for a new or increased appropriation of water if there is sufficient “unappropriated water” available in the source of supply [Texas Water Code §11.134(b)(2)]. Unappropriated water is defined in 30 Texas Admin. Code §297.1(54) of the TCEQ rules as the amount of state water remaining in a watercourse after taking into account all existing water rights valued at their full authorized amounts and conditions.

- Drought of record conditions are considered in the determination of water availability for new water rights associated with diversions and impoundments.
- To the extent practicable when considering all public interests, the TCEQ must include conditions in any permit and certain permit amendments, as necessary, to maintain existing instream uses and water quality.

Often, such conditions include certain specified minimum levels of streamflow that have to be passed downstream before any water can be used (diverted or impounded) for the new appropriation. These by-passed flows are intended to provide protection for downstream aquatic resources. The TCEQ performs studies of the potential impacts of new appropriations of surface water (and certain amendments of existing appropriations) on instream uses, fish and wildlife habitat, water quality, and bay and estuaries, and considers information available from the TPWD and other sources to establish appropriate restrictions and conditions that are included in new permits or permit amendments to reserve flows for environmental purposes.

The Texas Water Code §11.147 defines “beneficial inflows” for an estuary to mean a salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is necessary for 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 dependant. The definition of the estuarine habitat implies ecosystem management to protect important natural resources that provide economic benefit. In building models of natural resource-inflow relationships, the state agencies have focused on the commercial harvest, not the ecosystem and habitats that support the beneficial resources. Emerging scientific concepts emphasize the need for ecosystem management to protect habitats that support all natural resources.

- The Texas Water Code does not expressly authorize the TCEQ to grant water rights exclusively for: (1) instream flows dedicated to environmental needs or inflows to the state's bay and estuary systems, or (2) other similar beneficial uses [Texas Water Code §11.0235(d)].

However, this does not prohibit the TCEQ from issuing an amendment to an existing permit or certificate of adjudication to change the use to or add a use for instream flows dedicated to environmental needs or bay and estuary inflows [Texas Water Code §11.0237(a)].

- Protection of water rights during times of shortages relies on the honor system in most of the river basins in Texas.

The exceptions to the honor system are the water rights administration programs of the South Texas (Lavaca, Guadalupe, San Antonio, and Nueces Basins) and Rio Grande Watermasters. The TCEQ is in the process of establishing an additional watermaster program for the Concho Basin.

### **8.2.1.3 State Aquatic Biological Resources**

The physical, chemical, and biological characteristics of rivers and streams across the state reflect many geologic, hydrologic, and human influences—especially those associated with municipal, industrial, and agricultural development over the last century. East Texas riverine systems have comparatively more dependable flows and exhibit more diverse ecological communities than West Texas rivers. There are, nevertheless, many important aquatic ecological resources in watercourses of even the western arid areas of the state that warrant maintenance.

The diverse ecological characteristics of the seven major and several minor Texas estuarine systems are defined by climatic and streamflow gradients of decreasing precipitation and freshwater inflows from north to south and east to west. Salinities in Texas estuaries reflect the decrease of freshwater inflows from north to south—with Sabine Lake estuary at the most northeast extreme experiencing an average condition of about 5 parts per thousand salinity and the Laguna Madre estuary at the most southwest extreme averaging about 35 parts per thousand.

A characteristic coastal ecosystem along the Texas coast is defined by the physical environment (e.g., inflow and salinities) and the ecological services provided by organisms that create habitats (e.g., marshes, seagrasses, mangroves, and oyster reefs). Because coastal habitats provide the foundation for ecosystem productivity, simply protecting the habitats should provide protection for everything else in the ecosystem.

## **8.2.2 Charge 2. Evaluate the analytical tools and/or procedures that are used or available to assess the requirements for preservation, maintenance, or enhancement of aquatic resources and riparian habitat.**

### **8.2.2.1 Rivers and Streams**

There are two distinct methods that are used by the state agencies for estimating environmental flow needs for instream uses in rivers and streams: statistical desk-top techniques sometimes referred to as “standard setting” methods; and “comprehensive” methods involving intensive field studies and integrated biologic, physiographic, and hydraulic analyses. While site-specific environmental flow studies—including field data collection and modeling—have been conducted for a small number of water development projects on different streams in the State over the last



20 years, the level of investigative effort and the breadth of useful information regarding environmental flow needs for supporting instream uses lag considerably behind the bay and estuary freshwater inflow program.

- Primarily, only the major water development projects (reservoirs) in the state that have been authorized in the last 20 years or so have received comprehensive site-specific field studies and associated analytical investigations to establish environmental flow needs.

When considering permit applications for new appropriations of surface water and certain amendments of existing water rights, the TCEQ draws upon all relevant information to establish appropriate safeguards for satisfying environmental flow needs, but typically, in the absence of information from site-specific field studies, statistical desk-top techniques have been used to assess and determine minimum environmental flow levels. The Lyons method specifies monthly minimum environmental flows based on either 40% (October through February) or 60% (March through September) of the historical median daily-averaged flows by month (flows that are exceeded 50% of the time on a monthly basis). This is a statistical desk-top method that has been used extensively, and is continuing to be used, by the TCEQ as a default method to establish environmental streamflow restrictions (reservations) for permitting purposes. The Lyons method was originally developed from other environmental flow studies, primarily of mountainous rivers and streams in the western states, and later (1979) was partially validated for Texas streams based on a single set of data collected on the Guadalupe River below Canyon Dam. Hence, the appropriateness of applying the Lyons method to establish minimum environmental flow needs for rivers and streams across the entire state is questionable.

- Apparently, no investigations beyond those originally conducted by Bounds and Lyons in 1979 apparently have been undertaken for Texas rivers and streams in an effort to further validate the applicability of the Lyons method. Therefore, its scientific basis for application to Texas systems is quite limited.

State and regional water planning in Texas requires the use of the Consensus Planning Criteria (CPC) method to assess and establish the environmental flow requirements for all new water supply development strategies when site-specific field studies are not available or feasible during regional planning efforts. The CPC method is composed of multistage rules for passing streamflows through reservoirs and by diversion points to provide minimum flows for protecting downstream environmental uses. Environmental bypass flows are based on three categories of conditions: above-normal hydrologic conditions (Zone 1), below-normal hydrologic conditions (Zone 2), and drought conditions (Zone 3). The criteria for establishing the thresholds between the CPC method's three hydrologic zones and the minimum flows that are required to be passed downstream are subjective, and, to date, no studies have been conducted that verify the appropriateness of default thresholds for delineating the three zones or the default magnitudes of the three levels of bypass flows.

- The actual numerical criteria incorporated into the CPC method for establishing environmental flow conditions are based primarily on intuition regarding environmental flow needs, rather than site-specific field data and scientific principles.

While this method has been used for determining environmental flow needs for planning purposes, it has not been utilized to any significant degree for establishing the specific environmental streamflow restrictions that have been incorporated into new water rights permits or permit amendments.

Senate Bill 2 (77<sup>th</sup> Legislature, 2001) directed the TPWD, TWDB, and TCEQ to jointly establish and continuously maintain an instream flow data collection and evaluation program and to conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state's rivers and streams, necessary to support a sound ecological environment. Pursuant to the requirements of Senate Bill 2, the TPWD, TWDB, and TCEQ have prepared a Programmatic Work Plan and a Technical Overview of the Texas Instream Flow Studies describing the proposed approach for undertaking field work and data collection on priority stream segments throughout the state and for evaluating and determining appropriate environmental flow needs.

- The Texas Instream Flow Studies program currently is being reviewed by the National Academy of Science (NAS), and, according to the TWDB staff, a report from the NAS is due before the end of 2004.
- The Texas Instream Flow Studies program appears to encompass a comprehensive and scientific approach for establishing environmental flow needs on rivers and streams across the state. However, more extensive review and examination of the details of the program, which may not be fully developed until the program is under way, is needed in order to effectively and finally evaluate the program's responsiveness to the requirements of Senate Bill 2.

To date, the Texas Instream Flow Studies program has been developed primarily by state agency staff with little stakeholder input; however, the scope of the program calls for, and must include, stakeholder meetings and interaction and rigorous scientific review prior to the final adoption of the program and/or its methodologies and procedures. Key to the utility of the Texas Instream Flow Studies program is application of the scientific results to the formulation of the specific management goals. In perhaps overly simplistic terms, the concern is how much degradation of the riverine fish and wildlife resources is going to be tolerable, as defined through the quantification of these goals. Within the Texas Instream Flow Studies program, post validation on a basin-specific basis should be emphasized more forcefully, because of the importance of confirming the robustness of the methodology.

All methods used by the state for establishing instream flows for the protection and preservation of fish and wildlife resources—whether statistical desk-top analyses or comprehensive field studies and modeling—provide only an abstraction and simplification of the real and complex ecological systems in rivers and streams. Comprehensive methods to establish instream flows provide more scientifically defensible instream flow recommendations, but at the price of appreciably more resource commitment than the statistical desk-top methods.

Many instream flow methodologies are used in the United States and other countries that employ a variety of techniques and procedures for evaluating and establishing environmental flows for riverine systems—including some involving a combination of methods such as the use of a desk-

top method for establishing initial environmental flow values, an expert panel to review results and make decisions regarding what measures to implement, and adaptive management procedures to address scientific allowances for uncertainty. Some of these methodologies could be useful for addressing environmental flow issues until such time when more scientifically based information is available from the comprehensive Texas Instream Flow Studies program.

#### **8.2.2.2 Bays and Estuaries**

For nearly four decades, the TWDB has been in the process of developing the quantitative State Methodology for determining the necessary freshwater inflows to a Texas bay. The core of the State Methodology is a set of fitted relations of measures of commercial harvest versus inflow to the bay, and a computer program that determines the optimal pattern of monthly inflows. The TWDB performs this determination for several alternative goals of the optimization.

- An important feature of the determination of the optimal pattern of monthly inflows is that the optimum is constrained by upper and lower limits on the monthly inflows.

The TPWD reviews the optimum flow patterns determined by the State Methodology and selects the set considered most beneficial to the bay, a process it refers to as "verification." TPWD's selection of the recommended inflow regime may be based on quantitative or qualitative methods. Different procedures for selecting the recommended inflow regime have been used on different bay systems.

The State Methodology offers several procedural advantages: (1) it is quantitative; (2) it is capable of refinement and improvement to accommodate new scientific information; and (3) it is based on easily recognized and popular natural resources. The State Methodology has several deficiencies: (1) the measure of abundance used is commercial harvest (except for Sabine Lake), which has a poor relation to ecological health or soundness and ecological integrity; (2) the species studied, with a few exceptions, are highly mobile and migrate between the estuary and the Gulf; (3) the various statistical methods are questionable, including regression forms, statistical confidence, and definition of independent variables; (4) the optimum is mainly determined by the constraints, which are inadequately justified; (5) an optimum solution is not conventionally used in water management, nor is it clear how it can be used for establishing required freshwater inflows; and (6) the optimum solution bears no relation to actual harvests (the optimized variable) nor do the optimum patterns of inflow occur in the natural hydrology. While the state has invested considerable effort and expense into the research underlying the State Methodology, most of it is peripheral to the actual quantitative relations. Moreover, the method of quantitative determination has not been altered substantially since the version of the Methodology documented twenty years ago.

- The Coastal Fisheries Program of the TPWD—a biological sampling program which has been underway for 50 years in at least some of the Texas bays—is a bellwether effort that provides fundamental information about the ecological state of major ecosystem components of the Texas coast, and the TPWD is commended for its vision and resolve in establishing and sustaining this important activity.

The procedure the TPWD employs to select the "best" optimal inflow pattern (of several determined by the State Methodology) uses a combination of circulation and salinity simulations and analyses of its Coastal Fisheries data and other criteria that appear to be bay-specific. It is not "verification" in the sense that the word is used in scientific method. It is a comparative analysis of *minQ* and *maxH*, and favors the *maxH*, which always has the greater inflow to the bay. It does not address the question of what inflows are *necessary* for maintaining a sound ecological environment in the bay. While the circulation and salinity model—despite the substantial investment made in its development—is peripheral to the State Methodology, the TPWD does apparently rely upon it for its "verification" analysis, and the TWDB has used it in other studies of the Texas bays (such as evaluating effects of deepwater channels on salinity). This model is poorly documented, its verification is apparently poor, and for most of its history of development and use at the TWDB, the model code has not been made available to scientists for testing and evaluation.

- One of the most important questions relating to management of inflows to the Texas bays is unanswered by the State Methodology and the TPWD "verification" analysis: Namely, under drought conditions, what inflows must a bay receive to maintain its ecosystem over the long term?

Models and methodologies developed to accurately predict ecological sustainability in times of drought would address a major point of uncertainty within the current environmental debate.

The present State Methodology is overly based on the premise that the abundance and/or harvest of commercial species are dependent upon inflow and salinity. This method is too simplistic, and the existing data bases are too incomplete to allow this approach to provide protection for bay health. A more modern approach is ecosystem management. This approach recognizes that inflow dilutes seawater, but it also provides sediments, nutrients, and energy that all combine to create and sustain the habitats that support economically important benefits to the state. These benefits are in the form of ecological services provided by the coastal zone in general. The most important ecological services are commercial and recreational fisheries, non-fishing recreational opportunities, erosional buffers, nursery habitats, nutrient cycling, and natural self-cleansing of estuarine waters. All of this suggests that the foundation of the conceptual model behind the state's approach is sorely in need of updating.

Evaluation of the performance of the state's existing methodologies or to have confidence in the results from those methodologies is difficult without measuring the right indicators and continual review of the results. The net effect of the current methodologies and management strategies may be that they will not provide sufficient protection of the bay health for some ecosystems.

### **8.2.3 Charge 3. Identify ecological parameters or ecosystem characteristics to be considered in determining environmental flow needs for the state's surface water resources and identification of implementation options.**

#### **8.2.3.1 Rivers and Streams**

An important element of conserving biodiversity involves conserving diverse habitats in rivers and streams. Because diverse habitats are supported by variable, natural flow regimes, it is

important to ensure that the natural fluctuations in streamflows and in sediment supplies are maintained seasonally and between years. Flow levels, timing, and patterns influence physical processes, with sediment flushing, sediment transport, large woody debris transport, and stream channel formation and maintenance occurring over a range of moderate to high flows. Rivers and streams and their floodplains assimilate nutrients and organic matter from natural and human sources such as runoff and wastewater.

- A varied flow regime that mimics natural, historical patterns is the key to conserving the fish and wildlife resources within and adjacent to Texas rivers and streams.

Those environmental flows must include annual and seasonal variations to maintain the inherent complexity of habitats and physical-chemical conditions upon which biological communities depend. Flows during drought periods can be especially critical with respect to maintaining biological resources in rivers and streams.

### **8.2.3.2 Bays and Estuaries**

The major habitats in Texas bays and estuaries are wetlands, seagrasses, open bay bottoms, shorelines, and oyster reefs. Bay environmental health indicators include water quality, species abundance, biomass, and diversity, and other measures of other aspects of biological community function and composition. Preserving characteristic biodiversity allows an estuary to remain resilient to natural and man-made disturbances. Bay and estuary environmental indicators generally include estuarine organisms that respond to changes in salinity conditions caused by changes in freshwater inflow. Good environmental indicators include the abundance of key species, such as fish and bivalve populations, benthic organisms, plant communities, and disease organisms.

- Seasonal timing of freshwater inflows to bays and estuaries is critically important for providing proper conditions for reproduction and growth.
- Seasonal high-flow events, which promote reproduction and growth, must be of sufficient volume and duration to affect salinity along estuarine gradients.

If the goal is to protect ecosystem health or soundness, then studies must measure quantifiable indicators of ecosystem health. Commercial harvest is more affected by other factors (primarily economic, such as, employment rates, energy prices, market prices, and fishing regulations) than it is affected by inflow per se. In contrast, the habitats that sustain fisheries are directly affected by inflow. During the last 30 years, it has been convincingly established that the best indicators of ecological health are measures of ecosystem integrity. Some of the best indicators of ecosystem integrity are often the metrics of the structure of bottom dwelling plants and animal communities because they are relatively fixed in space and long-lived, which means they integrate ecosystem functions over long time scales.

## **8.2.4 Charge 4. Provide any other technical information the Science Advisory Committee feels would be beneficial to the Study Commission on Water for Environmental Flows.**

### **8.2.4.1 The Scientific Process**

At the core of the issue of environmental flows is a scientific problem: determining the effects of the movement of water (and everything that implies) on the biological communities of a water body. The reliability of this determination is dependent upon the adequacy of the underlying science.

The phenomena of concern to environmental flows are complex and not amenable to controlled experiments, which allow removal of undesired complexities. Observations in the various sciences involved in establishing environmental flows are logistically difficult and expensive, and tend to be sparse in space and time. There are numerous sources of error and natural variability, and many external variables affect the measurements, usually themselves not monitored, perhaps not even recognized. Adding to the complexity, many physical and biological processes relating to effects of environmental flows operate at different spatial and temporal scales—often at scales different from field monitoring programs. Because the influence of these variables cannot be eliminated, field measurements are intrinsically *uncontrolled*.

In the aquatic sciences, replication of measurements is strictly impossible because a field measurement and all of the prevailing external conditions cannot be exactly duplicated. The role of replication normally demanded in scientific method is replaced by one of *corroboration*, which focuses on the measurement protocols, handling of data, repetition of analyses, and evaluation of statistical variance in the data, all assuming that the basic readings of instruments are reported exactly.

- Corroboration is typically beyond the resources of individuals and requires a concerted and systematic effort by groups of scientists.

In the application of scientific results to societal issues, the nature of scientific progress as an incremental convergent process, combined with its intrinsic uncertainty ("error"), should be especially noted.

- At any point in time, the scientific answer to a practical question, such as the determination of flows necessary to sustain an aquatic ecosystem, is provisional and approximate.

This does not mean that the answer is useless. On the contrary, the entirety of applied science, including the disciplines of engineering, is founded upon such provisional results and (hopefully) is devoid of "science with an agenda." The role of science is to provide the best technical information available in an unbiased fashion.

- The confidence in a scientific answer must be appraised, including not only the probable range of error, but also the degree of corroboration that the underlying science has received.

There should also always be a continual questioning of the basic assumptions from which interpretations, “answers,” and model outputs are derived and corrections made where justified. Advisory committees comprised of scientific talent from universities, agencies, and the private sector would be beneficial during the development process for environmental flow methodologies, in assisting with interpretations of scientific databases, in providing professional guidance where data is lacking, and in reviewing environmental flow program implementation.

#### **8.2.4.2 Environmental Flow Issues**

There seems to be little disagreement that environmental flows are important and necessary for maintaining the ecological health of the state’s rivers and streams and its bays and estuaries; the question is: How much water is required, and in what temporal or spatial distributions, to assure that the state’s aquatic resources are adequately protected? Of course, if the answer to the “how much” question was clearly known, the equally important question would remain: How can these requirements for environmental flows be satisfied with the limited water supplies that are available in many parts of the State while still meeting the other important demands for water? The ecological resources of rivers and streams and those of the bays and estuaries are distinctly different, and their requirements for environmental flows likewise are very different. Hence, the state’s programs and procedures for evaluating and quantifying environmental flow needs for rivers and streams are vastly different than those for the bays and estuaries.

The ability to provide adequate quantities of water for environmental flows is complicated by competing demands, particularly for municipal and agricultural uses, and, of course, this problem is most pronounced in those basins that are fully appropriated or approaching a fully-appropriated condition with respect to existing available surface water resources versus authorized uses (water rights).

The inherent uncertainties associated with establishing environmental flow targets include: (1) lack of basic understanding regarding water-ecosystem interactions and relationships; (2) lack of useful data; (3) complex natural processes; and (4) the extreme variations and apparent randomness of weather events and other natural phenomenon, as well as uncertainties pertaining to the performance of the chosen strategy or strategies by which the environmental flow targets are to be achieved. The elements of uncertainty and risk relative to environmental flows can become an especially important component of the policy-making process in cases in which: (1) the potential damage of the activity could be large; (2) significant time and/or distance separates the activity and its impact; (3) incomplete knowledge exists regarding the nature and severity of the impact; and (4) sufficient monitoring and enforcement are unlikely.

The various uncertainties associated with environmental flows point toward an implementation strategy that provides responsive flexibility that allows for adjustments over time, as more information and understanding is obtained regarding the relationship of environmental flows to the ecosystem and the performance of the implementation strategy. This adaptive management approach can be achieved through an iterative process that involves: (1) choosing environmental

flow targets and the strategy by which the targets are to be pursued, even if significant uncertainty exists; (2) monitoring the impact of the target flows on the ecosystem, as well as the effectiveness of the strategy in achieving the targets; (3) learning from the new information gathered; and (4) implementing changes, adjustments, and revisions to the environmental flow targets, the implementation strategy, or both, based on the new information gathered.

In other areas of human or ecological health where there is a great deal of uncertainty, regulations are based on the precautionary principal. The precautionary principle involves setting rules at the most conservative level to protect human and environmental health during the period of uncertainty. If new information demonstrates that risks are sufficiently low at more liberal levels of protection, then changes are justified.

Adaptive management relative to environmental flows should work both ways; that is, if future science suggests that the adopted environmental flow targets are excessive and not necessary to sustain a sound ecological environment, then the targets should be reduced to allow other uses to be made of the excess flows, and vice versa. It is important to recognize, however, that simply agreeing to utilize an adaptive management approach does not ensure that appropriate environmental flow targets will be ultimately achieved. The complexities and conflicts associated with satisfying competing demands for water still have to be dealt with, and compromises among the different water users or uses often are necessary and unavoidable. What is important is to apply the best science available to arrive at the best estimate of environmental flow needs for a particular situation, and then to attempt to implement the strategies necessary to achieve these environmental flow targets while balancing all other interests and water demands. One way to accommodate the uncertainties inherent in the environmental flow targets through the adaptive management process is to establish reasonable and scientifically determined ranges on how much the targets can be changed (increased) in response to improved science or on how much the changes in the targets can affect (decrease) the dependable water supply of an associated water development project. Such limits would provide some degree of certainty and risk protection to water developers, while at the same time, providing for an initial base flow level, and an additional reserved amount, of environmental flow protection. These limits, however, have the potential to result in environmental flow targets that do not fully achieve desired soundness of the ecological environment. The key is to assure that rigorous and defensible science is applied on a case-by-case basis in order to derive the best estimates possible for the required environmental flow targets and the corresponding limits on changes to those targets.

### **8.2.4.3 Economic Considerations**

The economic benefits attributable specifically to environmental flows are closely linked with goods and services provided by the ecosystem, or by the water itself as a component of habitat. Water left instream to sustain the ecosystem may also be used for a variety of other purposes—such as recreation, navigation, hydroelectric generation, waste assimilation, conveyance to downstream points of diversion, and the provision of aesthetic beauty—that yield significant additional economic value.

Determination of economic impacts related to changes in environmental flows typically includes estimates of “direct” effects and may include estimates of secondary effects that result as these direct effects work their way through the economic system. For many uses of water, the price of



water is determined by the cost of providing it, rather than by the market forces of supply and demand. No price exists for some uses, including environmental flows. Analysis of the economic relationship of environmental flows and economic services is so early in its infancy that little is known about it, and few estimates of economic value have been derived from this relationship.

#### **8.2.4.4 Environmental Flow Strategies**

Implementation strategies for achieving desired levels of environmental flows can be generally grouped into two broad categories: (1) regulatory, those that utilize the legal and regulatory authority of the state to directly allocate water for environmental flows; and (2) market based, those that provide incentives for the free-trade marketing of water rights to accomplish the transfer or allocation of water for environmental purposes. The overall program for achieving environmental flow targets may consist of a combination of these two basic strategies. Regulatory environmental flow strategies include: (1) environmental flow reserves; (2) environmental flow permits; (3) environmental flow conditions attached to new water rights permits (and certain permit amendments); (4) water taxes; (5) reservation of return flows; and assertion of superceding public interest to acquire water for environmental flows. Market based environmental flow strategies include: (1) water markets; (2) water banks; and (3) water trusts.

All regulatory and market-based approaches to providing environmental flows have specific strengths and weaknesses. Environmental flow strategies that combine these two approaches can potentially take advantage of the “strengths” of the particular approaches, while offsetting or mitigating to the extent possible their respective “weaknesses.” Thus, combination strategies, if carefully crafted, can provide potential advantages over “single strategy” approaches. The state of Texas has utilized primarily the regulatory strategy, involving the attachment of environmental flow conditions to new water rights permits and certain permit amendments to achieve protection of environmental flows. It also has in place provisions for a water bank to facilitate the sale and transfer of existing water rights and a water trust to encourage the assignment and dedication of water authorized under existing water rights for environmental purposes. However, it is not evident that these approaches, as currently structured, are adequate to comprehensively and scientifically ensure target environmental flows.

The starting point relative to available, uncommitted water within a basin can matter a great deal in shaping the implementation strategy or strategies for providing for environmental flows. If insufficient unappropriated water exists, one of the main objectives of the implementation strategy is to “recover” water from existing permits (water rights). In this case, many of the regulatory approaches may prove to be politically difficult to implement, and very likely could result in legal challenges. Market-based strategies, by which the existing water right holders voluntarily enter into transactions by which their rights are converted or modified to provide for environmental flows, are likely to provide the best means to recover the necessary water to satisfy environmental flow requirements. Market-based strategies require financial resources to participate in the market sufficiently to obtain the target level of environmental flows. In the case where sufficient unappropriated water exists, regulatory approaches that allocate the water to fulfill environmental flow needs may prove to be efficacious strategies, with market-based strategies serving as a mechanism for adapting to the natural dynamics and inherent uncertainties associated with environmental flows.

## 9. LIST OF REFERENCES

- Adams, J.B., G.C. Bate, T.D. Harrison, P. Huizinga, S. Taljaard, L. van Niekerk, E.E. Plumstead, A.K. Whitfield, and T.H. Wooldridge. 2002. A method to assess the freshwater inflow requirements of estuaries and application to the Mtata Estuary, South Africa. *Estuaries* 25:1382–1393.
- Alber, M. 2002. A conceptual model of estuarine freshwater inflow management. *Estuaries* 25:1246–1261.
- Amirfathi, P.; Narayanan, R.; and Larson, D. 1984. A Methodology for Estimating Instream Flow Uses for Recreation. Logan, Utah: Water Research Laboratory, Utah State University.
- Annear, T., I. Chisholm, H. Beecher, A. Locke and 12 other authors. 2002. Instream flows for riverine resource stewardship. Instream Flow Council, Cheyenne, Wyoming.
- Bauer, C.J. 2004. *Siren Song: Chilean Water Law as a Model for International Reform*. Washington, D.C. Resources for the Future.
- Bauer, C.J. 1998. *Against the Current: Privatization, Water Markets, and the State in Chile*. Boston: Kluwer Academic Press.
- Berrens, R.P., Bohara, A.K., Silva, C.L., Brookshire, D., and McKee, M. 2000. 'Contingent values for New Mexico instream flows: With tests of scope, group-size reminder and temporal reliability'. *Journal of Environmental Management*, 58: 73–90.
- Bounds, R.L., and Lyons, B.W. 1979. Existing Reservoir and Stream Management Recommendations Statewide Minimum Streamflow Recommendations. Federal Aid Project F-30-R-4. Performance Report. Texas Parks and Wildlife Department, Austin, Texas. 28p.
- Bovee, K.D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. FWS/OBS-82/26, USFWS, Washington, D.C.
- Bowles, D.E., K. Aziz, and C.L. Knight. 2000. *Macrobrachium* (Decapoda: Caridea: Palaemonidae) in the contiguous United States: a review of the species and an assessment of threats to their survival. *Journal of Crustacean Biology* 20:158–171.
- Brajer, Victor and Martin, W. 1990. "Water Rights Markets: Social and Legal Considerations," *American Journal of Economics and Sociology*, vol. 49: 35–44.
- Colby, Bonnie. 1990a. "Enhancing Instream Flow Benefits in an Era of Water Marketing," *Water Resources Research*, vol. 26: 1113
- Colby, Bonnie. 1990b. "Transactions Costs and Efficiency in Western Water Allocation," *American Journal of Agricultural Economics*, vol. 72: 1184–1192.

- Colby, Bonnie. 1989a. "The Economic Value of Instream Flows – Can Instream Values Compete in the Market for Water Rights?" in L. MacDonnell, ed., *Instream Flow Protection: Law and Policy*. Boulder: University of Colorado Press.
- Colby, Bonnie. 1989b. "Estimating the Value of Water in Alternative Uses," *Natural Resources Journal*, vol. 28: 511–527.
- Connor, J.V. and R.D. Suttkus. 1986. Zoogeography of freshwater fishes of the western gulf slope of North America. Pages 413–456 in C.H. Hocutt and E.O. Wiley, editors. *The zoogeography of North American freshwater fishes*. John Wiley and Sons, New York.
- Costanza, R. 1992. Toward an operational definition of ecosystem health. In R. Costanza, B.G. Norton and B.D. Haskell, eds. *Ecosystem Health: New goals for environmental management*. Island, Press, Covelo, California.
- Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Bruello, R.G. Raskin, P. Sutton, M. van den Velt. 1997. "The Value of the World's Ecosystem Services and Natural Capital." *Nature* 287: 253–260.
- Cross, R., and D. Williams (eds.). 1981. *Proceedings of the National Symposium on Freshwater Inflow to Estuaries*. U.S. Fish and Wildlife Service, Office of Biological Services. FWS/OBS-81/04. 2 vols.
- Daily, Gretchen. 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Washington, D.C.
- Daubert, J. T. and Young, R. A. 1981. "Recreational Demands for Maintaining Instream Flows: A Contingent Valuation Approach," *American Journal of Agricultural Economics*, vol. 63: 666–676.
- Doering, P.H., R.H. Chamberlain, and D.E. Haurert. 2002. Using submerged aquatic vegetation to establish minimum and maximum freshwater inflows to the Caloosahatchie Estuary, Florida. *Estuaries* 25:1343–1354.
- Duffield, J.; Neher, C; and Brown, T. 1992. Recreation Benefits of Instream Flow: Application to Montana's Big Hole and Bitter Root Rivers," *Water Resources Research*, vol. 28: 2169–2181.
- Dyson, M., G. Bergkamp, and J. Scanlon (eds.). 2003. *Flow. The essentials of environmental flows*. International Union for Conservation of Nature and Natural Resources, Gland, Switzerland and Cambridge, UK. xiv + 118 pp.
- Edwards, R.J., G. Longley, R. Moss, J. Ward, R. Matthews, and B. Stewart. 1989. A classification of Texas aquatic communities with special consideration toward the conservation of endangered and threatened taxa. *The Texas Journal of Science* 41:231–240.
- Estevez, E.D. 2002. Review and assessment of biotic variables and analytical methods used in estuarine inflow studies. *Estuaries* 25:1291–1303.

- Flannery, M.S., E.B. Peebles, and R.T. Montgomery. 2002. A percent-of-flow approach for managing reductions of freshwater inflows from unimpounded rivers to the Southwest Florida estuaries. *Estuaries* 25:1318–1332.
- Gibbons, Diana C. 1986. *The Economic Value of Water*. Washington, DC: Resources for the Future.
- Greenly, D.; Walsh, R.; and Young, R. 1982. *Economic Benefits of Improved Water Quality*. Boulder: Westview Press.
- Howells, R. G., R.W. Neck, and H.D. Murray. 1996. *Freshwater mussels of Texas*. Texas Parks and Wildlife Department, Austin, Texas.
- Hubbs, C., R.J. Edwards, and G.P. Garrett. 1991. An annotated checklist of the freshwater fishes of Texas, with keys to identification of species. Supplement. *Texas Journal of Science* 43(4).
- Instream Flow Council. 2002. *Instream Flows for Riverine Resource Stewardship*. Instream Flow Council. 411p.
- Kimmerer, W.J. 2002. Physical, biological, and management responses to variable freshwater inflow into the San Francisco Estuary. *Estuaries* 25:1275–1290.
- Landry, Clay. 2003. *Review of Western U.S. Water Leasing Programs* (WestWater Research, LLC: Laramie, WY).
- Landry, Clay. 1998. *Saving Our Streams Through Water Markets: A Practical Guide*. (Political Economy Research Center, Bozeman, MT).
- Lee, Kai N. 1993. *Compass and Gyroscope: Integrating Science and Politics for the Environment*. Washington D.C.: Island Press.
- Linam, G.W., L.J. Kleinsasser, and K.B. Mayes. 2002. regionalization of the index of biotic integrity for Texas streams. River Studies Report No. 17. Texas Parks and Wildlife Department, Austin, Texas.
- Longley, W.L. (ed.). 1994. *Freshwater inflows to Texas bays and estuaries: ecological relationships and methods for determination of needs*. Texas Water Development Board and Texas Parks and Wildlife Department, Austin, Texas. 386 p.
- Loomis, J. 1987. “The Economic Value of Instream Flow: Methodology and Benefit Estimates for Optimal Flows,” *Journal of Environmental Management*, vol. 24: 169–179.
- MacDonnell, Lawrence J.; Rice, Teresa A.; and Shupe, Steven J. 1989, eds. *Instream Flow Protection in the West*. Boulder:
- Madariago, B. and McConnell, K. 1987. “Exploring Existence Value,” *Water Resources Research*, vol. 23: 936–942.
- Mathis, Mitchell. 2004. *The Economic Value of Water for Ecosystem Preservation: Ecotourism in the Texas Lower Rio Grande Valley*. Final Report to the Texas Coastal

- Management Program, General Land Office Contract No. 03-020. Houston Advanced Research Center, The Woodlands, Texas.
- McKinney, L., 2003: Why bays matter. *Texas Parks and Wildlife: the Outdoor Magazine of Texas* 61 (7), July 2003, pp. 23–25.
- Montagna, P.A., M. Alber, P. Doering, and M.S. Connor. 2002. Freshwater inflow: Science, policy, management. *Estuaries* 25:1243–1245.
- Montagna, P.A. and R.D. Kalke. 1992. The effect of freshwater inflow on meiofaunal and macrofaunal populations in the Guadalupe and Nueces Estuaries, Texas. *Estuaries* 15:266–285
- Montagna, P.A., Li, J., Street, G.T. 1996. A conceptual ecosystem model of the Corpus Christi Bay National Estuary Program Study Area. Corpus Christi Bay National Estuary Program, Publication CCBNEP-08. Texas Natural Resource Conservation Commission, Austin, Texas 114 pp.
- Montagna, P.A. and R.D. Kalke. 1995. Ecology of infaunal Mollusca in south Texas estuaries. *American Malacological Bulletin* 11:163–175.
- Moulton, D.W., T.E. Dahl and D.M. Dall. 1997. *Texas Coastal Wetlands: Status and Trends, Mid-1950s to early 1990s*. U.S. Fish and Wildlife Services, Austin, Texas. 32p.
- National Wildlife Federation. Unpublished. Summary Comparison of Methods to Ensure Environmental Flows in Texas.
- Orlando, S.P., L.P. Rozas, G.H. Ward, and C.J. Klein, 1993: *Salinity characteristics of Gulf of Mexico estuaries*. Office of Ocean Resources Conservation and Assessment, National Ocean Service, National Oceanic and Atmospheric Administration, Silver Spring, MD.
- Pierson, W.L., K. Bishop, D. van Senden, P.R. Horton, and C.A. Adamantidis. 2002. Environmental water requirements to maintain estuarine processes. Environmental Flows Initiative Technical Report Number 3, Commonwealth of Australia, Canberra.
- Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, and others. 1997. “That Natural Flow Regime: A Paradigm for River Conservation and Restoration,” *Bioscience*. Vol. 47(11): 769–784.
- Pulich, W., J. Tolan, W. Lee and W. Alvis, 2002: *Freshwater inflow recommendation for the Nueces estuary*. Resource Protection Division, Texas Parks and Wildlife Department, Austin, Texas.
- Randall, A. 1983. “The Problem of Market Failure,” *Natural Resources Journal*, vol. 23: 131–148.
- Random House, Inc. 1997. Random House Webster’s College Dictionary. New York, New York.
- Rapport, D., Costanza, R. and McMichael, A.J. 1998. Assessing ecosystem health. *TREE* 13(10):397–402.
- Richter, B. D., J. V. Baumgartner, R. Wigington, and D. P. Braun. 1997. How much water does a river need? *Freshwater Biology* 37:231–249.

- Richter, B. D., R. Mathews, D. L. Harrison, and R. Wigington. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* 13:206–224.
- Robinson, E. H. 1969. A procedure for determining desirable streamflows for fisheries. U.S. Fish Wildl. Serv., Mimeo Rep. 12p.
- Schulze, W.; Brookshire, D.; Walther, E.; MacFarland, K.; Thayer, M.; Whitworth, R.; Ben – David, S.; Malm, W.; and Molenar, J. 1983. “The Economic Benefits of Preserving Visibility in the National Parklands of the Southwest,” *Natural Resource Journal*, vol. 23: 149–163.
- Seibert, Elizabeth; Young, Doug; and Young, Mike. 2000. Market-Based Opportunities to Improve Environmental Flows. Scoping Report to Environment Australia. Policy and Economic Research Unit, CSIRO Land and Water, Australia.
- Stein, Bruce. 2002. States of the Union: Ranking America’s Biodiversity. Arlington, Virginia: Nature Serve. 25.
- Tennant, D.L. 1976. Instream flow regimes for fish, wildlife, recreation and related environmental resources. *Fisheries* 1(1):6–10.
- Texas Parks and Wildlife Department, 1979. *An Analysis of Texas Waterways*. Austin, Texas.
- Tharme, R.E. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* 19:397–441.
- U.S. Water Resources Council. 1978. The Nation’s Water Resource 1975-2000. Washington, D.C.: U.S. Government Printing Office.
- Walsh, R.; Loomis, J.; and Gilman 1984. “Valuing Option, Existence and Bequest Demand for Wilderness,” *Land Economics*, vol. 60: 14–29.
- Walsh, R.; Ericson, R.; Arosteguy, D; and Hansen, M. 1980. “An Empirical Application of a Model for Estimating the Recreation Value of Instream Flow.” Colorado Water Resources Research Institute Completion Report No. 101, Fort Collins: Colorado State University.
- Wilkinson, C. 1986. “Public Interest Constraints on Water Transfers,” in S. Shupe, ed. *Water Marketing: Opportunities and Challenges of a New Era*. Denver: University of Denver Press.
- Wurbs, R.A. 2003. “Water Rights Analysis Package (WRAP) Modeling System Reference and Users Manuals.” Texas Water Resources Institute, Technical Reports 255 and 256, College Station, Texas.