Texas Instream Flow Studies: Technical Overview

Report 369
May 2008

Texas Commission on Environmental Quality
Texas Parks and Wildlife Department
Texas Water Development Board

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1 *Executive Summary*

Senate Bill 2, enacted in 2001 by the 77th Texas Legislature, established the Texas Instream Flow Program, which is jointly administered by the Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board (hereafter referred to as "the Agencies"). The purpose of the program is to perform scientific and engineering studies to determine flow conditions necessary for supporting a sound ecological environment in the river basins of Texas. This document identifies a process for developing and conducting those studies.

To accomplish the program's goals, flow regimes that promote ecological integrity and maintain biodiversity will be determined, with the understanding that maintaining the physical habitats, water quality, and hydrologic character of specific river sub-basins will contribute to a sound ecological environment. In consultation with stakeholders, study-specific goals and objectives consistent with the definition of a sound ecological environment will be determined. These definitions will be compatible with all applicable state and federal laws, as well as statewide goals of the Texas Instream Flow Program.

Studies for specific river sub-basins will be conducted as shown in Figure 1-1. Activities listed above the horizontal line in Figure 1-1 are components of the Senate Bill 2 authorization for the Texas Instream Flow Program. Those activities are described in more detail in Tables 1-1 through 1-4 and throughout this document.

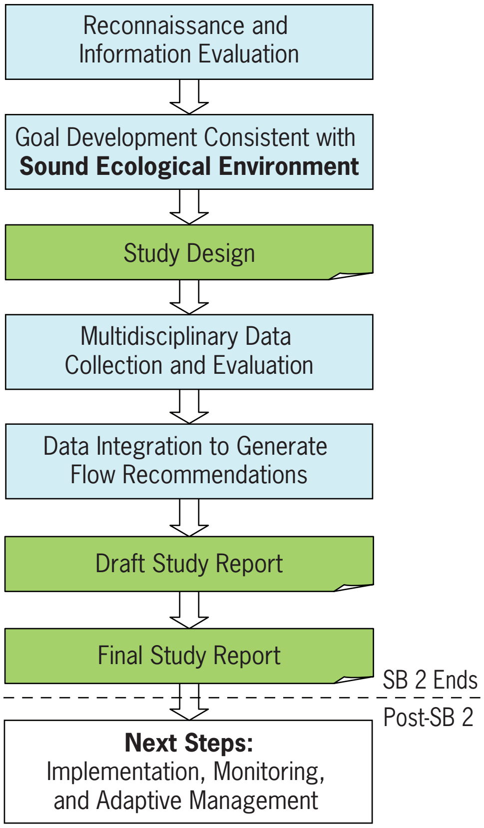


Figure 1-1. Steps in sub-basin studies of the Texas Instream Flow Program.

The geographic vastness of Texas results in a wide diversity of aquatic ecosystems. Within the context of overall program goals and objectives, methods and procedures for technical studies in support of instream flow recommendations will need to be tailored for each individual system. The study approach adopted for the instream flow program focuses on the flow requirements of the entire riverine ecosystem. Studies will be multidisciplinary in nature, including the disciplines of hydrology and hydraulics, biology, geomorphology, and water quality. Studies will also address connectivity and linkages between each discipline. Multidisciplinary studies will be integrated to develop a flow regime composed of several flow components such as subsistence and base flows, high flow pulses, and overbank flow components as shown in Figures 1-2 through 1-5. Flow components will be identified for wet, average, and dry hydrologic conditions, as appropriate.

The Texas Instream Flow Program

Table 1-1. Summary of sub-basin study activities during Step 1.

Step 1: Reconnaissance and Information Evaluation

Purpose

- Compile, review, and georeference available studies/data.
- Identify historic and current conditions, significant issues, and concerns.
- Conduct preliminary field surveys and analysis.

Data Sources

- U.S. Geological Survey and other gage data.
- Federal/state/local studies and reports.
- Historic air photos/Digital Orthographic Quarter Quadrangle/maps/soil surveys.
- Current water quality models and standards.

Activities

Stakeholder Participation

- Provide historic and current perspective of resource.
- Identify important concerns and opportunities for study participation.
- Select sub-basin workgroup.

Hydrology and Hydraulics

- Calculate flow statistics for historic and existing conditions.
- Identify existing features (such as tributaries) and existing and proposed alterations (for example, diversions, impoundments, and land uses) affecting hydrologic character.

Biology

- Identify historic and current species assemblages, representative macro- and meso-habitat types, and other biological issues and considerations.
- Assess historic and current condition of stream biota and riparian resources.
- Identify potential study reaches and sites.

Geomorphology

- Analyze aerial photography and other historic data as available.
- Assess channel bed form and banks, active channel and floodplain processes, and changes in sediment regime and causes.
- Make preliminary geomorphic classification of river segment.

Water Quality

- Assess historic and current water quality and aquatic life uses.
- Identify water quality issues and constituents of concern.

Output

- Synthesized summary of available studies/data, including GIS layers.
- Conceptual models describing the relationships between ecological health and flow regime.
- Prioritized list of research needs to address identified knowledge gaps.

Scale: All Scales

Table 1-2. Summary of sub-basin study activities during Step 2.

Step 2: Goal Development and Study Design

Purpose

- Develop sub-basin goals and objectives consistent with a sound ecological environment.
- Create study design, including descriptions of intensive study sites, specific technical tools and sampling criteria, and target flow ranges and seasons for field data collection.

Data Sources

- Goals and objectives of agencies, cooperators, and stakeholders.
- Results of reconnaissance activities from Step 1.

Activities

Stakeholder Participation

- Sub-basin workgroup assists Agencies in developing study design.

Hydrology and Hydraulics

- Determine data collection requirements for hydraulic modeling to support biological, geomorphic, and water quality studies.
- Assess hydraulic conditions within study sites.

Biology

- Confirm location of key/representative habitats within study sites.
- Choose appropriate sampling methods and estimate resource requirements.

Geomorphology

- Determine appropriate methods subject to constraints (including available historical data).
- Confirm presence of suitable geomorphic features within study sites.

Water Quality

- Confirm location of key water quality areas of concern within study sites.
- Assess need for additional water quality modeling and determine data collection requirements.

Output

- Study design consistent with Technical Overview.

Scale: All Scales

has been designed so that instream flow studies may be conducted by qualified third parties with the Agencies' oversight. In that event, this document will serve as a general overview of the requirements of such a study. This document does not provide sufficient guidance to meet all the varied conditions that may be encountered in Texas. Those conducting studies will need to be in communication with the Agencies to review and approve necessary adaptations of the methods described in this document.

Table 1-3. Summary of sub-basin study activities during Step 3.

Step 3: Multidisciplinary Data Collection and Evaluation

Purpose

- Collect input data required for models and analyses.
- Continuously monitor water quality and flow conditions at study sites.
- Determine relationships between flow, water quality, biology, habitat, channel, and floodplain conditions.

Data Sources

- Hydrologic measurements and bathymetric mapping.
- Biological data collection and habitat mapping.
- Geomorphic data collection and mapping.
- Water quality data collection.

Activities

Stakeholder Participation

- Sub-basin study and data collection workshops/field demonstrations.

Hydrology and Hydraulics

- Monitor stage/discharge continuously during study period.
- Map substrate, woody debris, and variations in hydraulic roughness.
- Model hydraulic characteristics in relation to flow, including extent of inundation associated with flood events.

Biology

- Collect appropriate biological and habitat use data.
- Describe habitat criteria and significant conditions for key species/guilds/life stages.
- Conduct habitat modeling to assess habitat-flow relationships, including diversity.
- Conduct riparian studies and estimate riparian requirements.

Geomorphology

- Develop sediment budgets.
- Identify factors controlling geomorphic behavior of river segment.
- Assess channel adjusting and overbank flow behavior, including flow conditions that initiate sediment and large woody debris movement and deposition.

Water Quality

- Monitor water quality at site during study period.
- Validate previous models and conduct water quality modeling studies as needed.
- Assess flow/water quality relationships.

Output

- Documentation of methods and data (hardcopy and electronic formats).
- Habitat versus flow relationships.
- Flows required to maintain water quality and channel/riparian areas.
- Refined conceptual models that describe ecological health and flow regime.

Scale: Study Sites

Table 1-4. Summary of sub-basin study activities during Step 4.

Step 4: Data Integration to Generate Flow Recommendations

Purpose

- Construct instream flow regime (including subsistence, base, and overbank flows and high flow pulses) that best meets sub-basin goals and objectives.

Data Sources

- Results of previous studies from Step 1.
- Sub-basin study goals and objectives from Step 2.
- Results of multidisciplinary studies from Step 3.

Activities

Stakeholder Participation

- Sub-basin workgroup provides input on data synthesis and interpretation.
- Review and comment on study report.

Hydrology and Hydraulics

- Calculate occurrence of various flow rates during historical and current conditions.
- Determine annual variability of hydrologic characteristics, including description of wet, average, and dry hydrologic conditions.
- Develop hydrologic time series to evaluate habitat suitability of proposed flow regime.
- Calculate variability of proposed flow regime and compare with historic/current conditions.
- Evaluate how proposed flow regimes would impact current operating conditions.

Biology

- Develop flow ranges at appropriate temporal scales for key species/guilds/life stages.
- Construct habitat time series for historic, current, and proposed flow regimes.

Geomorphology

- Estimate, if possible, historic channel conditions.
- Evaluate consequences of various flow regimes for channel/riparian areas.
- Estimate feasibility of alternative intervention actions.

Water Quality

- Identify flow conditions that satisfy key water quality/biology relationships.
- Consider water quality issues related to proposed flow regime components.

Output

- Instream flow study report, including description of flow recommendations, ecological significance of flow components, and study methods and analysis.

Scale: River Segment

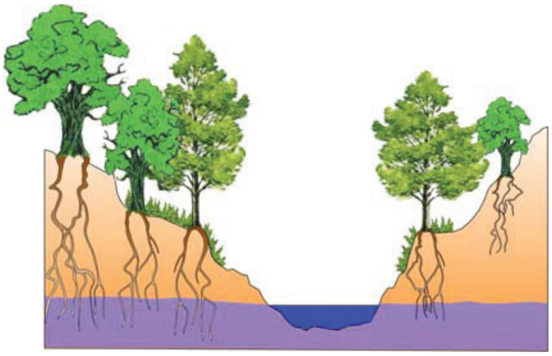
Subsistence Flows

Spatial scale:
River Reach

Temporal scale:
Hourly Flow, Varies from Month to Month

Primary discipline:

- 🟦 Hydrology/Hydraulics
- 🟩 Biology
- 🟧 Geomorphology
- 🟥 Water Quality



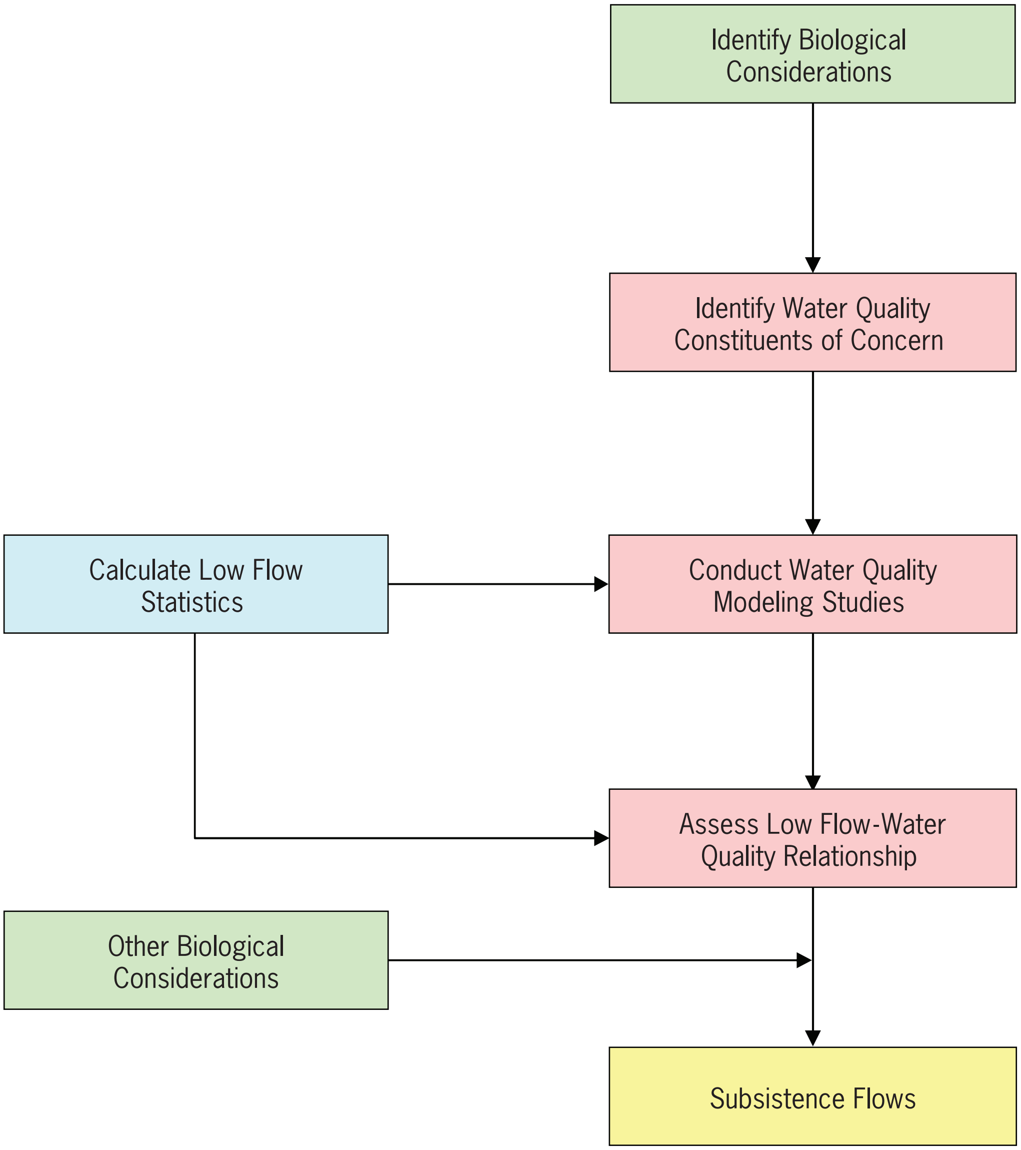


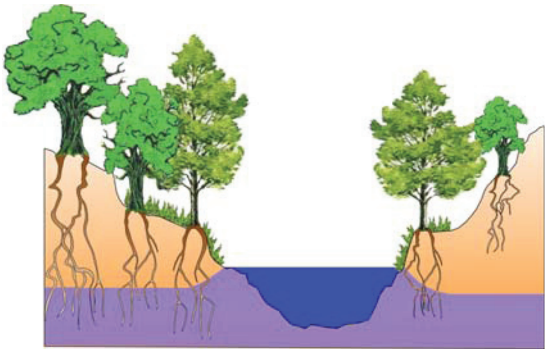
Figure 1-2. Development of subsistence flow recommendations from results of multidisciplinary activities.

Base Flows

Spatial scale:
River Reach

Temporal scale:
Daily Flow Range, Varies from Month to Month

Primary discipline:
🟦 Hydrology/Hydraulics
🟩 Biology
🟧 Geomorphology
🟥 Water Quality



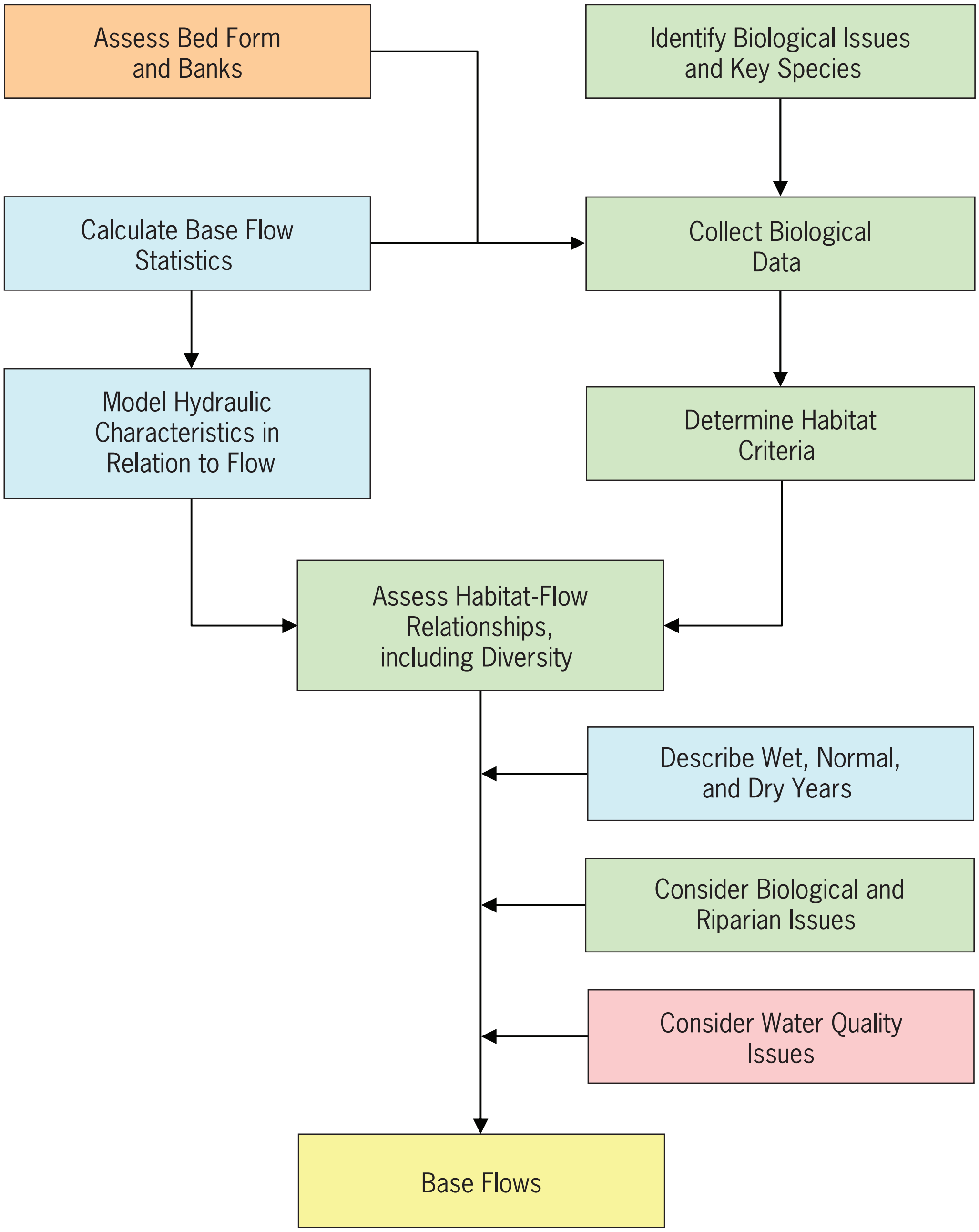


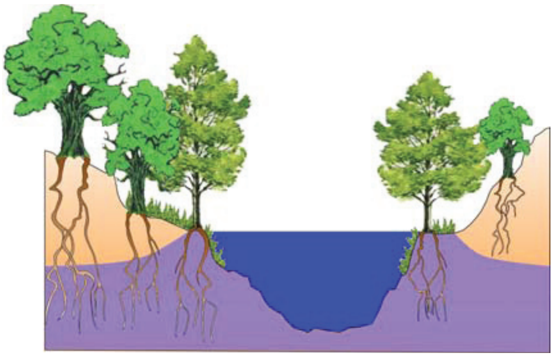
Figure 1-3. Development of base flow recommendations from results of multidisciplinary activities.

High Flow Pulses

Spatial scale:
River Segment

Temporal scale:
Multiple High Flow, Pulses Throughout the Year

Primary discipline:
🟦 Hydrology/Hydraulics
🟩 Biology
🟧 Geomorphology
🟥 Water Quality



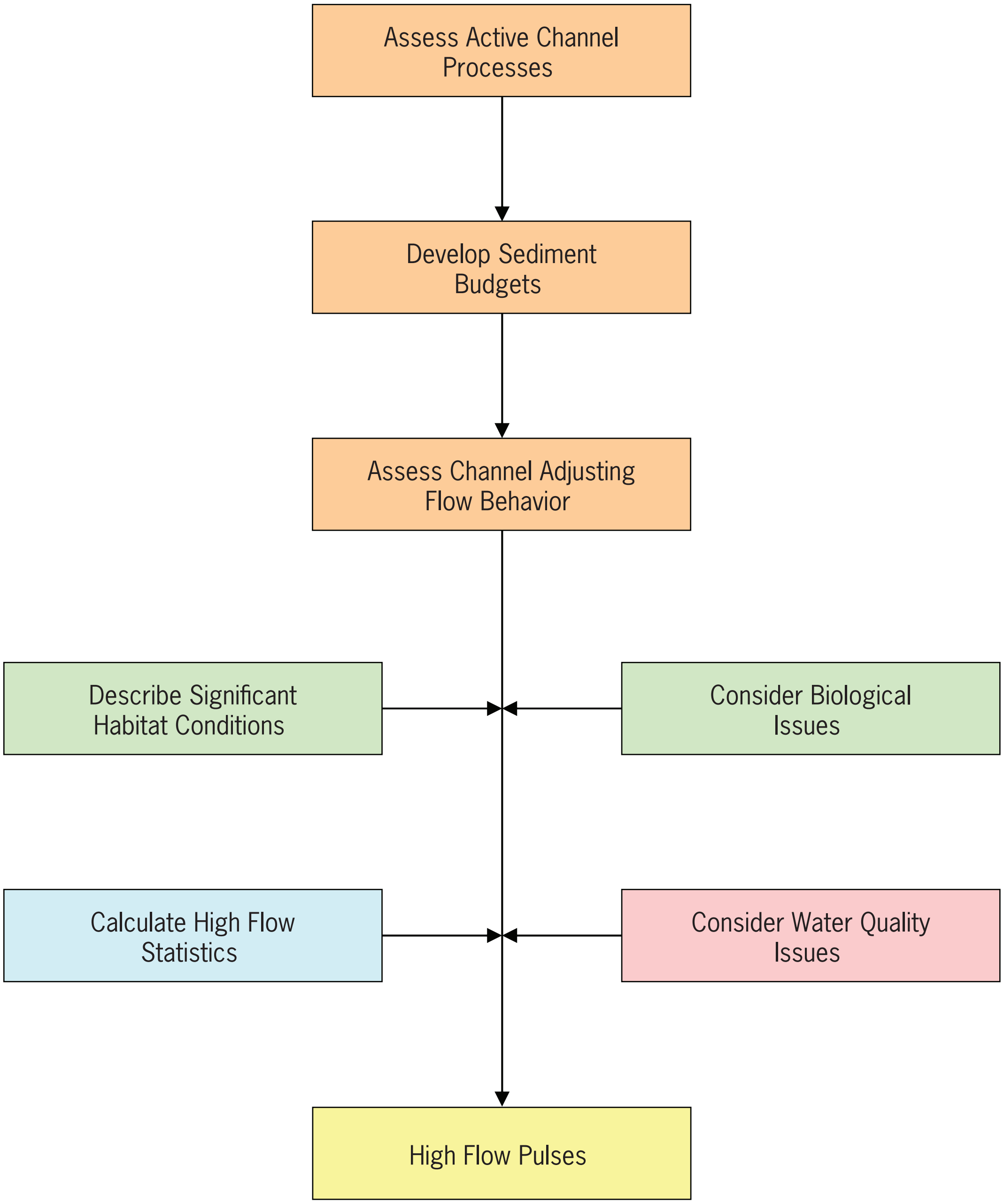
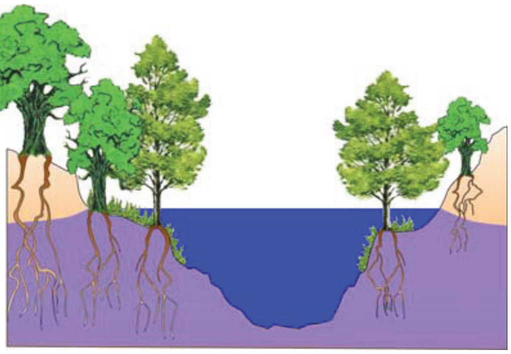


Figure 1-4. Development of high flow pulse recommendations from results of multidisciplinary activities.

Overbank Flows



Spatial scale:
River Segment

Temporal scale:
Extreme Flow Events, Occur Less Than Once per Year

Primary discipline:

- 🟦 Hydrology/Hydraulics
- 🟩 Biology
- 🟧 Geomorphology
- 🟥 Water Quality

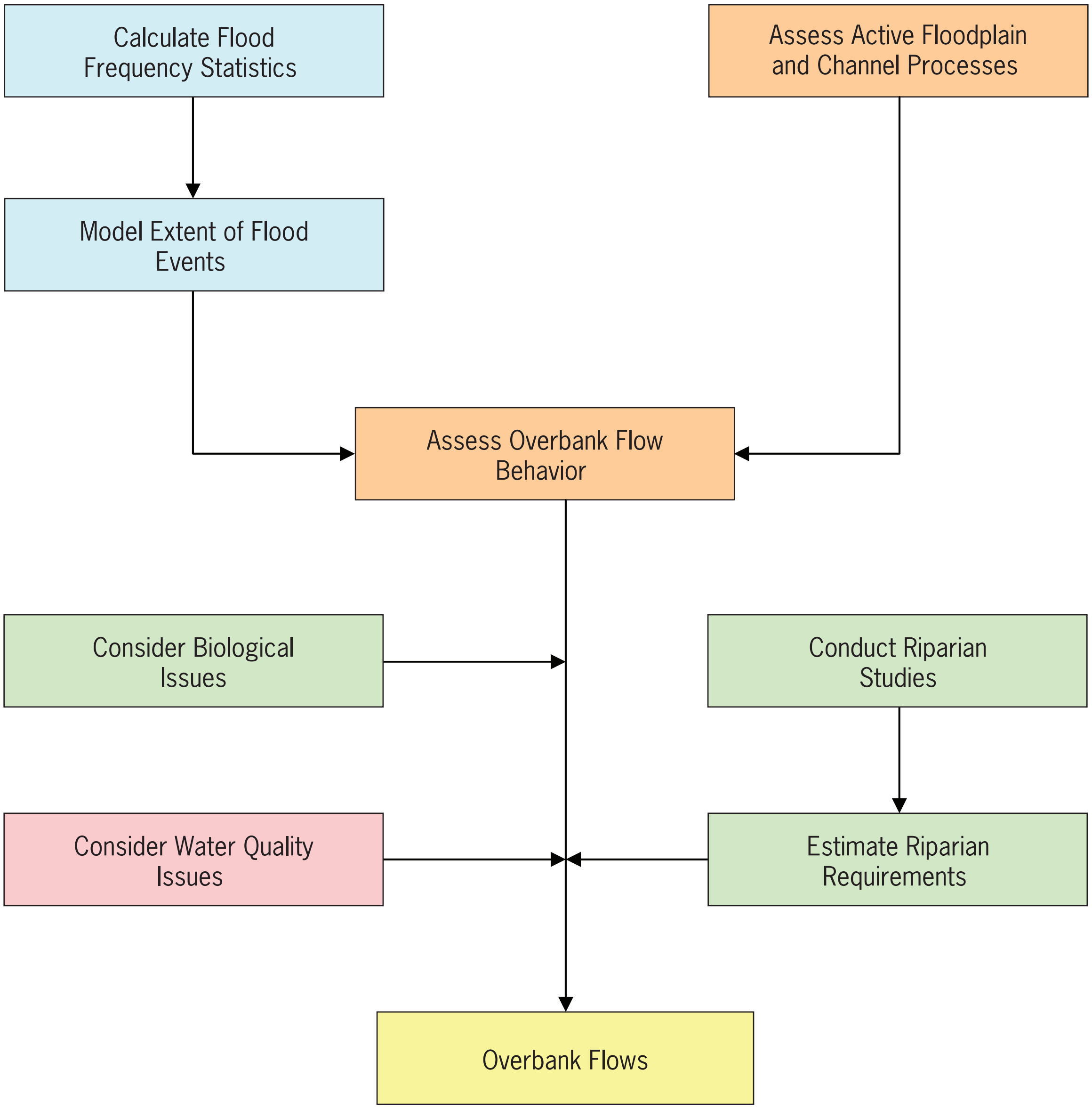


Figure 1-5. Development of overbank flow recommendations from results of multidisciplinary activities.

2 *Introduction*

In 2001, the 77th session of the Texas Legislature enacted Senate Bill 2 establishing the Texas Instream Flow Program. The program is being cooperatively developed and jointly administered by the Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board (hereafter referred to as "the Agencies"). Its purpose is to perform scientific and engineering studies to determine flow conditions necessary to support a sound ecological environment in the river basins of Texas. This document identifies a process for developing and conducting those instream flow studies.

The urgency and seriousness with which the state embarks upon this program to determine instream flow requirements is not to be underestimated. At stake are much of the state's irreplaceable natural resources and water supplies for its citizens, economy, and environment. The population of Texas is expected to nearly double in the next 50 years, from almost 21 million people in the year 2000 to about 46 million in 2060 with attendant shortages of water (TWDB, 2007). If the state does not ensure sufficient water to meet projected needs, socioeconomic models predict reduced economic growth and vitality (TWDB, 2007). Additionally, the impact on hunting and fishing could be tremendous. Sansom (1995) states that

> Texas ranks first among the states in hunting opportunities and second in fishing. It is today the number one destination in the world for birdwatchers. The impact of these activities on the economy of the state is substantial: In 1993 alone, visitors to Texas state parks spent nearly $200 million, while hunters, anglers, and other wildlife enthusiasts spent almost $4 billion.

Further, the health and maintenance of various riparian areas, hardwood bottomlands, and associated wetland ecosystems are intimately linked to instream flows. For example, instream flows affect the volume of nutrients and organic materials from both natural and human sources that can be assimilated by rivers and riparian areas. They also affect the tremendous diversity of plants and animals, several of which are known to occur exclusively in Texas, that depend on rivers, streams, and riparian areas.

2.1
HISTORY OF TEXAS INSTREAM FLOW PROGRAM

Senate Bill 2 directs the Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board (the Agencies) to "jointly establish and continuously maintain an instream flow data collection and evaluation program…" In addition, the legislation directed the Agencies to "conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state rivers and streams necessary to support a sound ecological environment." In response to this directive, the Agencies developed the Texas Instream Flow Program.

In October 2002, the Agencies signed a Memorandum of Agreement, which provided an operating agreement among the Agencies and established an Instream Flow Studies Coordinating Committee comprising the Agencies' executive leadership and an Interagency Science Team of staff scientists and engineers. We completed a Programmatic Work Plan for the instream flows program in December 2002 (TIFP, 2002). The Work Plan identified priority studies and interim deadlines for publications, outlined the roles of the state agencies, and presented the scope of the studies and general methods for conducting the studies. In August 2003, the Agencies completed a precursor to this document, a draft Technical Overview of Texas instream flow studies, which provided an in-depth discussion of the methods proposed for use by the Texas Instream Flow Program.

In June 2003, we submitted the Work Plan and draft Technical Overview to the National Research Council of the National Academy of Sciences as part of a scientific peer review. They completed the review in February 2005 and documented their results in a report (NRC, 2005). After revising the Technical Overview in response to the recommendations of the National Research Council, the Agencies submitted it for stakeholder evaluation in May 2006. The Agencies have incorporated recommendations and comments from that evaluation in this document.

Additional information about the Texas Instream Flow Program is available at this Web site: www.twdb.state.tx.us/instreamflows/index.html

2.2
TEXAS INSTREAM FLOW PROGRAM APPROACH TO SUB-BASIN STUDIES

The Texas Instream Flow Program will conduct sub-basin studies that focus on the entire ecosystem, are subject to scientific realities, and reflect a larger program context. The program will maintain a focus on the overall riverine ecosystem by conducting multidisciplinary studies, considering a range of spatial and temporal scales, focusing on essential ecosystem processes, and recommending a flow regime to meet study goals and objectives. The program will consider scientific realities by recognizing that instream flows are only part of the requirements for a sound ecological environment. Study results will acknowledge and document uncertainty. As scientific understanding of the issues surrounding instream flow requirements deepens, procedures and methods employed in the program will need to adapt and change over time. In order to fit within its program context, the Texas Instream Flow Program will be transparent to the public, involve stakeholders and scientific peers, and strive for compatibility with existing programs related to environmental monitoring and protection of Texas streams and rivers.

2.2.1
Ecosystem Focus

Senate Bill 2 gives the Texas Instream Flow Program a mandate to identify instream flow conditions that support a "sound ecological environment" without precisely defining this term. However, Senate Bill 2 was adopted in the context of the existing state statutes shown in Table 2-1. These statutes make clear that the activities of the Agencies must provide adequate water quality and fish and wildlife habitat, link terrestrial and riparian habitats to the aquatic environment, and consider both short- and long-term consequences. In response to Senate Bill 2 and these statutes, the Agencies have adopted an approach for the program that focuses on entire riverine ecosystems and have proposed the following definition for a sound ecological environment:

> A resilient, functioning ecosystem characterized by intact, natural processes and a balanced, integrated, and adaptive community of organisms comparable to that of the natural habitat of a region.

Ensuring a sound ecological environment requires maintaining the ecological integrity and conserving the biological diversity of a riverine ecosystem. To meet these goals, the Agencies recognize that it is important to maintain the natural

Table 2-1. Environmental considerations related to streams/rivers as directed by state statutes.

Consideration	Statute
will not cause…adverse impact on…the environment of the stream	30 TAC 297.45(b)
no adverse impact to…the environment	30 TAC 297.45(d)
assess the effects…on fish and wildlife habitats...consider whether the proposed project would affect river or stream segments of unique ecological value	30 TAC 297.53(a)
mitigate adverse impacts, if any, on fish and wildlife habitat	30 TAC 297.53(b)
assessment…shall include the project site as well as potentially impacted habitat upstream, adjoining, and downstream	30 TAC 297.53(c)
…"no net loss" of wetland functions and values	30 TAC 297.53(e)
In addition to aquatic and wildlife habitat, wetland functions also include, but are not limited to, water quality protection through sediment catchment and filtration, storage plans for flood control, erosion control, groundwater recharge, and other uses.	
shall examine both direct and indirect impacts to terrestrial and riparian habitats, as well as long- and short-term effects to the watershed or ecoregion	30 TAC 297.53(f)6
assess the effects…on water quality of the stream or river…consider the maintenance of State of Texas Surface Water Quality Standards…and the need for all existing instream flows to be passed up to that amount necessary to maintain the water quality standards for the affected stream	30 TAC 297.54(a)
to protect fish and wildlife resources, including permit conditions, mitigation, and schedules of flow or releases	TPWC 12.024(b)
conditions considered…necessary to maintain existing instream uses and water quality of the stream or river	TWC 11.147(d)
conditions considered…necessary to maintain fish and wildlife habitats	TWC 11.147(e)
shall assess the effects…on water quality in this state	TWC 11.150
assess the effects…on fish and wildlife habitats and may require…reasonable actions to mitigate adverse impacts	TWC 11.152
determine the potential impact…on…instream uses	TWC 16.012(k)

TAC=Texas Administrative Code
TPWC=Texas Parks and Wildlife Code
TWC=Texas Water Code

habitat diversity, hydrologic character, and water quality of river systems.

Because of their complexity, it is widely accepted that riverine ecosystems require multidisciplinary studies (see, for example, Palmer and others, 2003; Wohl and others, 2005). Components related to hydrology, geomorphology, biology, water quality, and connectivity must be considered in order to adequately address flow requirements of aquatic ecosystems (Annear and others, 2004). As a result, the Texas Instream Flow Program will follow this multidisciplinary conceptual model.

In addition, instream flow studies require a multiscale approach because riverine ecosystems have many components that interact across a range of scales. Spatial scales of riverine ecosystems range from molecular interactions of water quality constituents to basinwide processes affecting sediment supply to the channel. Temporal scales may range from less than a few hours for some chemical processes to thousands of years or longer for geologic changes in the watershed. In response, the Agencies have developed an approach that considers a range of spatial and temporal scales.

An ecosystem approach also requires the Texas Instream Flow Program to focus on essential ecological processes. Riverine ecosystems are complex systems of interacting abiotic and biotic components. To manage these systems effectively, at least a basic understanding of these interactions (such as food web dynamics, reproductive cues, species recruitment, and colonization) is required. Attempting to manage a riverine ecosystem without adequate understanding of such processes can be problematic. For example, many river restoration projects in California have been unnecessary, unsuccessful, or even detrimental because essential riverine processes were not understood (Kondolf, 1998). Understanding the essential processes of a specific river ecosystem will undoubtedly require conducting a number of technical studies covering different disciplines.

Instream flow recommendations will be in the form of flow regimes containing several components. Because they occur over a range of flows, essential riverine ecosystem processes cannot be preserved by a single "minimum" flow rate. Although the outcome of many instream flow methods are single-flow recommendations, Annear and others (2004) concluded that such recommendations have not succeeded in adequately maintaining riverine ecosystems.

River scientists now recognize that a range of flows are required to maintain healthy riverine ecosystems (Brown and King, 2003; Schofield and others, 2003). Based on the results of technical studies, the instream flow program will identify a set of flow components that support important processes (Table 2-2). In general, there should be some correspondence between instream flow recommendations and historical hydrologic patterns for a sub-basin.

2.2.2
Scientific Realities

While conducting sub-basin studies, the Agencies will be aware of scientific realities. We recognize the important, but not exclusive, role that flows play in supporting a sound ecological environment. We also recognize that knowledge and understanding of riverine ecosystems are imperfect, and as a result, study findings will incorporate uncertainty. As understanding of these ecosystems increases, the procedures and methods used to develop flow recommendations for Texas rivers will need to adapt and change.

Because almost every process in riverine ecosystems is flow related, instream flows play an important part in creating a sound ecological environment. In most cases, implementing adequate instream flows should result in the riverine environment meeting its ecological goals. But adequate timing

Table 2-2. Example components of an instream flow regime and supported processes.

Component	Hydrology	Geomorphology	Biology	Water quality
Subsistence flows	Infrequent, low flows	Increase deposition of fine and organic particles	Provide restricted aquatic habitat Limit connectivity	Elevate temperature and constituent concentrations Maintain adequate levels of dissolved oxygen
Base flows	Average flow conditions, including variability	Maintain soil moisture and groundwater table Maintain a diversity of habitats	Provide suitable aquatic habitat Provide connectivity along channel corridor	Provide suitable in-channel water quality
High flow pulses	In-channel, short duration, high flows	Maintain channel and substrate characteristics Prevent encroachment of riparian vegetation	Serve as recruitment events for organisms Provide connectivity to near-channel water bodies	Restore in-channel water quality after prolonged low flow periods
Overbank flows	Infrequent, high flows that exceed the channel	Provide lateral channel movement and floodplain maintenance Recharge floodplain water table Form new habitats Flush organic material into channel Deposit nutrients in floodplain	Provide new life phase cues for organisms Maintain diversity of riparian vegetation Provide conditions for seedling development Provide connectivity to floodplain	Restore water quality in floodplain water bodies

Sources: Adapted from MEA (2005); NRC (2005).

and quantity of instream flows may not be enough to ensure ecosystem goals are met because instream flow regimes in and of themselves are not sufficient to maintain the ecological condition of a river (Schofield and others, 2003). The instream flow program will identify factors in addition to flow alteration that affect whether ecosystem goals for river segments in the study are attained. Such factors may include both human activities (Table 2-3) and the recent occurrence of natural disturbances, such as extreme floods and droughts or hurricanes. The Agencies will report and quantify these additional factors and their ecological effects as is practical within time and budget constraints.

Scientific studies of river ecosystems are conducted in the field on complex systems that are imperfectly understood. As such, they are subject to the vagaries of field conditions (changing climatic conditions, natural variability in species abundances, and fluctuations in disturbance regimes) and limitations in scientific understanding. Results are inherently uncertain. To the extent possible, the Agencies will quantify the uncertainty in study results and make this information

Table 2-3. Human activities that may affect riverine ecosystems.

Category	Activities		
Watershed	Vegetative clearing Land use change Hard surfacing	Overgrazing Land grading Urbanization	Soil exposure or compaction Irrigation and drainage Roads and railroads
Channel	Streambank armoring Utility crossings	Channelization Dredging	Streambed disturbance Woody debris removal
Structural	Dams and levees Bridges	Storm water discharge outlets	Reduction of floodplain
Flow alteration	Withdrawal of water	Increased return flows	Changed magnitude and timing of peak flows
Species	Biotic harvesting	Exotic species	
Pollution	Point source	Diffuse	

Sources: Adapted from FISRWG (1998); Giller (2005).

available to decision makers, stakeholders, and the public.

Because of scientific uncertainty, the Agencies strongly endorse the concept of adaptive management. Within the context of adaptive management, implementation of instream flow results will be monitored to see whether the established goals are being reached. If goals are not met, an adaptive process would be invoked to adjust implementation measures. Procedures for implementing instream flow recommendations in Texas should be capable of evaluating the effectiveness of instream flows and refining and adapting the flow regime as necessary. As stated by King and Brown (2003),

> a monitoring program is particularly important given the generally poor understanding of the links between flow and ecological response. The implementation of an agreed flow regime should allow for adaptive management based on the monitoring. The monitoring program should be designed to provide essential feedback on whether the:
>
> - agreed-upon flow is being released
> - overall objective (desired river condition) is being achieved
> - objectives for different components of the regime are being met
> - environmental flow allocation needs to be modified in light of the observed responses.

Through time, the Agencies will adapt and change study procedures and methods as necessary to improve the program. At first glance, it would seem advantageous to examine all of the primary study areas in Texas with one identical set of methods and procedures suitable for all conditions because this would facilitate comparing results from one study to the next. However, given the diversity of Texas river systems, one set of tools may not be sufficient. Because each basin represents a unique set of features or issues, established methods and procedures may need to be refined and varied in order to study all of the major rivers of Texas. The Agencies expect to gain significant understanding of large riverine ecosystems during initial studies of these systems. This understanding will be used to refine methods and procedures for future studies.

2.2.3
Program Context

The Agencies recognize that the Texas Instream Flow Program will function within a broader context that includes political and socioeconomic concerns and other government programs related to managing river ecosystems. The program will be conducted in the public view, and the Agencies will develop sub-basin goals, objectives, and study designs with stakeholder input. In addition, peers from the scientific community will provide reviews of study designs and reports. We expect the peer review process to increase public confidence in study results and, therefore, the likelihood that flow recommendations will be implemented.

The Agencies also recognize that the instream flow program will be conducted within the broader context of federal, state, and local activities that affect, regulate, or monitor rivers within Texas. The program will use data from these programs for evaluating and monitoring river ecosystems. We will evaluate and incorporate the results of any pertinent research efforts completed by other parties. To the extent possible, study objectives will be structured to take advantage of ongoing programs. For example, water quality investigations will be structured to complement or rely on existing Texas Commission on Environmental Quality water quality programs conducted in partnership with local river authorities. The goal will be to build the instream flow program in conjunction with existing activities rather than to create an entirely new process or duplicate existing efforts. This should reduce expense, redundancy, and conflicting regulation while improving ecosystem understanding.

2.3
LAYOUT OF TECHNICAL OVERVIEW

Identifying a process to develop instream flow studies for major Texas river sub-basins is not a trivial task, and there are few models available for guidance. Few programs have attempted to apply procedures to a range of conditions as diverse as those found in Texas. (Chapter 3 of this document describes the general complexity of riverine ecosystems and the diversity of ecological conditions across the state.)

The process of identifying instream flows for Texas' rivers must be robust, that is, suitable in any river basin yet adaptable to the specific conditions of every river basin. Study procedures may need to vary significantly from one river basin to another. Any description of such a process represents a trade-off between providing detailed guidance required to conduct a specific study and general guidance applicable to a range of conditions. This document is intended to describe the general framework of the process. It does not provide an exhaustive list of the conditions that might be encountered during instream flow studies in Texas. It does, however, describe the organizational process the Agencies will follow to assess available data, set goals, conduct studies, integrate results, develop and implement recommendations, monitor river conditions, and adapt recommendations as necessary. It also describes the general technical capabilities that the Agencies can provide in support of instream flow studies.

The overall process the Agencies will follow in a sub-basin instream flow study is shown in Figure 2-1. Individual steps in the process are also described in Tables 2-4 through 2-7. The first step in the process involves reconnaissance of the specific sub-basin and evaluation of previously collected data (Table 2-4). The Agencies, with the assistance of cooperators and/or contractors, will assemble and evaluate available data for the river system. These data may include results of monitoring, research, and study efforts conducted by the Agencies, other state and federal agencies, universities, and/or other organizations. This first step will be completed with the help of stakeholders, including local river authorities, who are likely to possess or have knowledge of data related to a specific river segment. We will supplement previously collected data and the current understanding of the river ecosystem with reconnaissance activities and preliminary analysis.

The main objective of this step is to develop a conceptual model based on available information of the relationship between ecological health and flow regime. Research efforts needed to address identified knowledge gaps will also be prioritized. Activities related to this step are discussed in Chapters 4 and 5.

The second step of a sub-basin instream flow study is to develop goals consistent with a sound ecological environment and other statewide goals and objectives. Activities will be a cooperative effort of the Agencies and stakeholders for the specific sub-basin (Table 2-5). The Agencies will present the current understanding of the condition and behavior of the river ecosystem, as well as the potential for improving that condition. Stakeholders and the Agencies will develop objectives for the desired condition of the river and goals and objectives for reaching and/or maintaining that desired condition. To measure progress toward the desired river condition, a set of ecological indicators will also be selected. The Agencies will develop plans for technical studies to determine the relationship of the instream flow regime to the ecological condition of the river within the sub-basin. With stakeholders, we will select potential study sites and evaluate their suitability. The final result of this step will be a study design describing sub-basin goals and objectives, ecological indicators, and methods and procedures for the technical studies. The study design will be submitted for scientific peer review and modified as necessary. Activities in this step are discussed in Chapters 4 and 5.

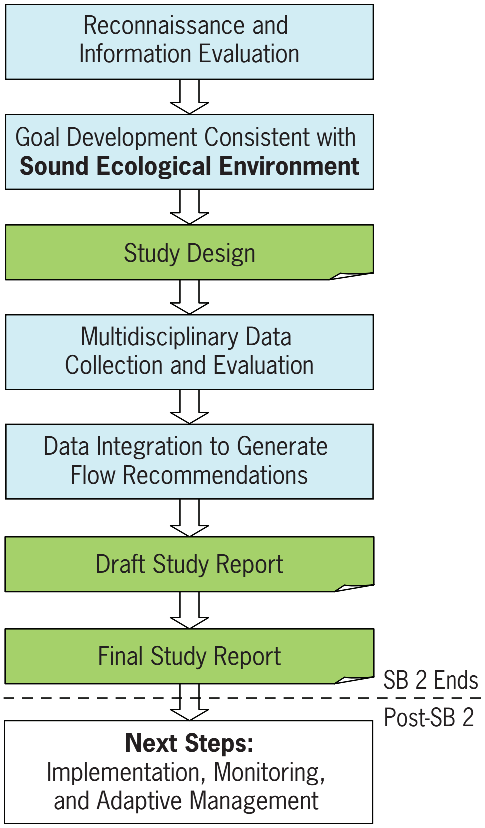


Figure 2-1. Steps in sub-basin studies of the Texas Instream Flow Program.

The third step is multidisciplinary data collection and evaluation accomplished by technical studies of the river ecosystem (Table 2-6). The Agencies and/or their contractors will conduct these studies, with input/assistance from stakeholders and in accordance with the study design agreed upon with stakeholders and finalized after scientific peer review. The Agencies will coordinate efforts to make efficient use of staff, expertise, and resources. Studies will not only be multidisciplinary, but also interdisciplinary in nature. To collect data across the desired range of flow and seasonal conditions, it will be necessary to conduct studies over more than one year. Several river segment studies will be conducted simultaneously to maximize efficiency. For example, when hydrologic and/or seasonal conditions

Table 2-4. Summary of sub-basin study activities during Step 1.

Step 1: Reconnaissance and Information Evaluation

Purpose

- Compile, review, and georeference available studies/data.
- Identify historic and current conditions, significant issues, and concerns.
- Conduct preliminary field surveys and analysis.

Data Sources

- U.S. Geological Survey and other gage data.
- Federal/state/local studies and reports.
- Historic air photos/Digital Orthographic Quarter Quadrangles/maps/soil surveys.
- Current water quality models and standards.

Activities

Stakeholder Participation

- Provide historic and current perspective of resource.
- Identify important concerns and opportunities for study participation.
- Select sub-basin workgroup.

Hydrology and Hydraulics

- Calculate flow statistics for historic and existing conditions.
- Identify existing features (such as tributaries) and existing and proposed alterations (diversions, impoundments, and land uses) affecting hydrologic character.

Biology

- Identify historic and current species assemblages, representative macro- and meso-habitat types, and other biological issues and considerations.
- Assess historic and current condition of stream biota and riparian resources.
- Identify potential study reaches and sites.

Geomorphology

- Analyze aerial photography and other historic data as available.
- Assess channel bed form and banks, active channel and floodplain processes, and changes in sediment regime and causes.
- Make preliminary geomorphic classification of river segment.

Water Quality

- Assess historic and current water quality and aquatic life uses.
- Identify water quality issues and constituents of concern.

Output

- Synthesized summary of available studies/data, including GIS layers.
- Conceptual models describing the relationships between ecological health and flow regime.
- Prioritized list of research needs to address identified knowledge gaps.

Scale: All Scales

are unfavorable on one river segment, data collection efforts will be focused on a different river segment where conditions are more favorable. Coordination of multidisciplinary studies is described in Chapter 5. The activities of individual disciplines are described in Chapters 6 through 9.

The fourth step of a sub-basin instream flow study is data integration to generate flow recommendations. Activities in this step are outlined in Table 2-7. Using the results of technical studies, the Agencies, with stakeholder input, will develop recommendations for an instream flow regime to meet study

Table 2-5. Summary of sub-basin study activities during Step 2.

Step 2: Goal Development and Study Design

Purpose

- Develop sub-basin goals and objectives consistent with a sound ecological environment.
- Create study design, including descriptions of intensive study sites, specific technical tools and sampling criteria, and target flow ranges and seasons for field data collection.

Data Sources

- Goals and objectives of agencies, cooperators, and stakeholders.
- Results of reconnaissance activities from Step 1.

Activities

Stakeholder Participation

- Sub-basin workgroup assists Agencies in developing study design.

Hydrology and Hydraulics

- Determine data collection requirements for hydraulic modeling to support biological, geomorphic, and water quality studies.
- Assess hydraulic conditions within study sites.

Biology

- Confirm location of key/representative habitats within study sites.
- Choose appropriate sampling methods and estimate resource requirements.

Geomorphology

- Determine appropriate methods subject to constraints (including available historical data).
- Confirm presence of suitable geomorphic features within study sites.

Water Quality

- Confirm location of key water quality areas of concern within study sites.
- Assess need for additional water quality modeling and determine data collection requirements.

Output

- Study design consistent with Technical Overview.

Scale: All Scales

objectives. This will require synthesizing study results across several spatial and temporal scales as well as between disciplines. The Agencies will present results as a range of flows over seasons and years, quantifying to the greatest extent possible the ecological consequences of deviations from these targets. A study report will include documentation of raw data, collection procedures, methods of analysis, and conclusions. It will also describe the uncertainties related to study results and the ecological risk associated with that uncertainty. The report will be submitted for scientific peer review and modified as needed. The peer review process is described in Chapter 4. Procedures to integrate study results and generate flow recommendations are discussed in Chapter 10.

The purpose of the Texas Instream Flow Program authorized by Senate Bill 2 is to perform scientific and engineering studies to determine instream flow conditions necessary to support a sound ecological environment in a specific sub-basin. Activities that occur after instream flow recommendations are developed,

Table 2-6. Summary of sub-basin study activities during Step 3.

Step 3: Multidisciplinary Data Collection and Evaluation

Purpose

- Collect input data required for models and analyses.
- Monitor water quality and flow conditions continuously at study sites.
- Determine relationships between flow, water quality, biology, habitat, channel, and floodplain conditions.

Data Sources

- Hydrologic measurements and bathymetric mapping.
- Biological data collection and habitat mapping.
- Geomorphic data collection and mapping.
- Water quality data collection.

Activities

Stakeholder Participation

- Sub-basin study and data collection workshops/field demonstrations.

Hydrology and Hydraulics

- Monitor stage/discharge continuously during study period.
- Map substrate, woody debris, and variations in hydraulic roughness.
- Model hydraulic characteristics in relation to flow, including extent of inundation associated with flood events.

Biology

- Collect appropriate biological and habitat utilization data.
- Describe habitat criteria and significant conditions for key species/guilds/life stages.
- Conduct habitat modeling to assess habitat-flow relationships, including diversity.
- Conduct riparian studies and estimate riparian requirements.

Geomorphology

- Develop sediment budgets.
- Identify factors controlling geomorphic behavior of river segment.
- Assess channel adjusting and overbank flow behavior, including flow conditions that initiate sediment and large woody debris movement and deposition.

Water Quality

- Monitor water quality at site during study period.
- Validate previous models and conduct water quality modeling studies as needed.
- Assess flow/water quality relationships.

Output

- Documentation of methods and data (hardcopy and electronic formats).
- Habitat versus flow relationships.
- Flows required to maintain water quality and channel/riparian areas.
- Refined conceptual models that describe ecological health and flow regime.

Scale: All Scales

including implementation, monitoring, and adaptive management, are not addressed by Senate Bill 2 and are not described in detail in this document.

Implementation is, however, arguably the most important step in an instream flow effort. Without it, previous steps are rendered ineffectual and a sound ecological environment is not protected. Adaptive management is widely recognized as a necessary approach for managing complex ecosystems and is considered

Table 2-7. Summary of sub-basin study activities during Step 4.

Step 4: Data Integration to Generate Flow Recommendations

Purpose

- Construct instream flow regime (including subsistence, base, and overbank flows and high flow pulses) that best meets sub-basin goals and objectives.

Data Sources

- Results of previous studies from Step 1.
- Sub-basin study goals and objectives from Step 2.
- Results of multidisciplinary studies from Step 3.

Activities

Stakeholder Participation

- Sub-basin workgroup provides input on data synthesis and interpretation.
- Review and comment on study report.

Hydrology and Hydraulics

- Calculate occurrence of various flow rates during historical and current conditions.
- Determine annual variability of hydrologic characteristics, including description of wet, average, and dry hydrologic conditions.
- Develop hydrologic time series to evaluate habitat suitability of proposed flow regime.
- Calculate variability of proposed flow regime and compare with historic/current conditions.
- Evaluate how proposed flow regimes would impact current operating conditions.

Biology

- Develop flow ranges at appropriate temporal scales for key species/guilds/life stages.
- Construct habitat time series for historic, current, and proposed flow regimes.

Geomorphology

- Estimate, if possible, historic channel conditions.
- Evaluate consequences of various flow regimes for channel/riparian areas.
- Estimate feasibility of alternative intervention actions.

Water Quality

- Identify flow conditions that satisfy key water quality/biology relationships.
- Consider water quality issues related to proposed flow regime components.

Output

- Instream flow study report, including description of flow recommendations, ecological significance of flow components, and study methods and analysis.

Scale: River Segment

to be a foundational component of a state-of-the-art instream flow program (NRC, 2005). An effective monitoring program is required in order to validate implementation and is integral to adaptive management. Senate Bill 3, passed in 2007 by the 80th Texas Legislature, sets up a process for the critically important activities of implementing, monitoring, and adaptively managing environmental flow recommendations based on the best available science. This includes, when available, results of studies completed by the Texas Instream Flow Program.

3 *Ecological Setting*

Given the wide diversity of aquatic ecosystems in Texas (Edwards and others, 1989), the geographical vastness of the state, and the different characteristics among and within river basins, the tools used to sample, model, and otherwise identify instream flows necessary to maintain a sound ecological environment will be tailored to each sub-basin, consistent with the overall goals of the Texas Instream Flow Program.

3.1
OVERVIEW OF DIVERSITY OF TEXAS

A series of maps illustrate the relevant characteristics of Texas. The *Physiographic Map of Texas* shows the physiographic provinces and provides information on topography, geologic structure, and bedrock types (BEG, 1996a). The *River Basin Map of Texas* depicts the watershed boundaries of the major river basins and the patterns of annual rainfall, in addition to information on watershed area, reservoirs, and factors influencing river basin character (BEG, 1996b). The *Major Texas Aquifers and Minor Texas Aquifers* maps delineate major and minor aquifers (TWDB, 1990a and 1990b). The *Geology of Texas* map depicts the geology of Texas and provides a synopsis of geologic history (BEG, 1992). The *Vegetation/Cover Types of Texas* map delineates the categories of vegetation and cover types. It also provides information on natural and human factors affecting plant associations, species richness, and the ecological regions of the state (BEG, 2000). *The Land-Resource Map of Texas* delineates land resources based on groundwater recharge, mineral, physical property, land form, dynamic process, and biological resource (wetland) units. It also summarizes information on the importance and use of each unit (BEG, 1999). These maps may be found at this Web site: www.lib.utexas.edu/maps/texas.html

Texas has approximately 307,385 kilometers (191,000 miles) of low- to medium-gradient, warm water streams and rivers. Most Texas rivers originate within the boundaries of the state and flow into the bays and estuaries bordering the Gulf of Mexico after traversing several different physiographic regions and biotic provinces. Rainfall varies from more than 127 centimeters (50 inches) per year in the east to less than 25 centimeters (10 inches) per year in the west. Although the base flows of some Texas rivers and streams are groundwater dependent (spring-fed), most streamflows are directly related to episodic rainfall-runoff events. Other stream segments are dominated by wastewater return flows from municipal areas.

Collectively, Texas' rivers and streams are biologically diverse, to some degree resulting from the wide range of topography, plant communities, and geology found within the state's borders. A recent publication on biodiversity in the United States indicates that overall, Texas ranks second in diversity, third in endemism, and fourth in extinctions of flora and fauna (Stein, 2002). Streams and rivers provide habitat for more than 255 species of fish, of which more than 150 are native freshwater species (Hubbs and others, 1991). Native fish communities consist entirely of warm water species, and their diversity reflects transitions from a Mississippi Valley fauna in the north and east to a Rio Grande fauna in the south and west (Conner and Suttkus, 1986). Consequently, East Texas rivers have much more diverse communities than rivers in West Texas (Edwards and others, 1989; Linam and others, 2002). The native stream fish fauna in Texas is composed mainly of cyprinids (minnows), percids (darters and perches), catostomids (suckers), centrarchids (sunfishes and basses), ictalurids (catfishes), and members of nearly 20 other families. More than 50 species of unionid mussels inhabit Texas rivers, streams, canals, reservoirs, lakes, and ponds (Howells and others, 1996). Mussel populations in Texas are commercially valuable (shell harvesting) yet little studied. Aquatic invertebrates in Texas streams are diverse, but this fauna remains lightly documented, and it is possible that the number of species of aquatic invertebrates occurring throughout the state numbers in the thousands. In addition, the biogeographic origins of the faunal elements found in Texas streams are equally diverse, with known representatives from the Gulf Coastal Plain, Chihuahuan Desert, Great Plains, and the Neotropics. Similar to the fishes, invertebrate diversity and densities are higher in eastern Texas when compared to those of the western portion of the state. Texas also has its share of nonnative species that inhabit aquatic environments. The most problematic of these include riparian, submerged, and floating plants, aquatic snails, mussels and clams, fish, and mammals.

The physical, chemical, and biological characteristics of the river basins reflect many geologic, hydrologic, and human influences, especially those associated with municipal, industrial, and agricultural development over the last century. No major river in Texas remains completely free flowing or free from nonpoint or point source pollution. Instream and riparian habitats have been altered by land use practices, channel modifications, and changes to hydrologic regimes from dam construction and operation, surface water diversion, and groundwater pumping. All of the major rivers in Texas are regulated to some extent by the water supply operations of the 196 major reservoirs (defined as those with a conservation storage capacity greater than 5,000 acre-feet or about 6.2 million cubic meters). Some of these reservoirs also provide flood control and generate hydroelectric power. Nonnative species introductions have altered the composition of lotic assemblages and in some instances have negatively influenced native species within a drainage or subdrainage. Two recent assessments document changes in Texas fish assemblages (Anderson and others, 1995; Hubbs and others, 1997).

3.2
OVERVIEW OF RIVERINE COMPONENTS

The Senate Bill 2 mandate to develop instream flow recommendations that maintain a sound ecological environment in rivers and streams clearly dictates that the function and structure of aquatic ecosystems must be preserved. To this end, the scope of studies will address the riverine components of biology, hydrology and hydraulics, water quality, and geomorphology. Connectivity, scale, and dimension (see Section 3.3) are also important because these riverine components interact within complex spatiotemporal dimensions and across scales to create and maintain the structure and function of lotic systems. Thus, a successful instream flow program will require an interdisciplinary approach to address these complex systems in a scientifically sound and comprehensive manner.

3.2.1
Biology

The biological component of instream flow studies includes developing an understanding of relationships between aquatic communities, life histories, and habitats (instream or riparian). It must also include an understanding of the physical processes that create and maintain system habitat, water quality, and hydrology (Bovee and others, 1998; Annear and others, 2004). Riverine communities include freshwater and estuarine fishes; other vertebrates, such as turtles; invertebrates, such as caddisflies, stoneflies, mayflies, and dragonflies; mollusks, such as mussels and snails; crustaceans, such as crayfish and river shrimp; aquatic macrophytes and algae; and riparian flora and fauna. Some are obligate riverine species requiring flowing water habitat for all or part of their life cycle. Others are habitat specialists that require specific substrates, current velocities, or depths. Riverine obligates and habitat specialists are generally well suited as target species for instream flow evaluations.

Hydrology plays a key role in determining the composition, distribution, and diversity of aquatic communities since many riverine biota have evolved life history strategies that correspond to the natural flow regime, that is, the magnitude, duration, frequency, timing, and rate of change of flow conditions (Poff and Ward, 1989; Richter and others, 1996). Flow regimes largely determine the quality and quantity of physical habitat available to aquatic organisms in rivers and streams (Bunn and Arthington, 2002). Habitat conditions are generally characterized in terms of current velocity, depth, substrate composition, and instream cover, such as large woody debris, undercut banks, boulders, macrophytes, and other cover types (Bovee and others, 1998). Habitat complexity (heterogeneity) is a primary factor affecting diversity of fish assemblages (Gorman and Karr, 1978; Angermeier, 1987; Bunn and Arthington, 2002), and heterogeneous habitats offer more possibilities for resource (niche) partitioning (Wootton, 1990). Flow regimes also influence physical (geomorphology) and chemical (water quality) conditions in rivers and streams, which, in turn, influence biological processes.

Water quality is interrelated with flow, has a major influence on aquatic biota, and varies widely across the state. For example, conductivity may range from 100 microsiemens per centimeter in East Texas to more than 100,000 in some West Texas streams. Altering the flow regime may change water quality and create a system that favors a noncharacteristic assemblage. Elevated water temperatures or depressed dissolved oxygen concentrations can lead to fish kills or uninhabitable zones or may favor tolerant species.

The life history and ecology of lotic organisms must be considered in evaluating instream flows. Using fish as an example, the fundamental aspects of interest are growth, survival, and reproductive success (spawning and recruitment). Information on foraging behavior, habitat use, the timing of those activities (nocturnal versus daytime), and temperature regime is essential to understanding growth. Data on habitat use of prey species may also provide valuable information. Ensuring reproductive success involves many habitat considerations (current velocity, depth, substrate composition and embeddedness, cover, and area) for spawning adults, eggs, fry, and juveniles. Spawning behavior or reproductive mode (Johnston, 1999) and water quality issues, such as temperature cues, are also important in ensuring reproductive success. Other issues (such as migration patterns) associated with life history strategies may be important in some systems.

Temporal considerations (spawning season, timing of peak flows, and photoperiod) also relate to life history strategies (Stalnaker and others, 1996). With respect to interannual (between years) variation in flows, short-lived fishes may require certain flows every year while populations of long-lived fishes may be sustained by meeting flow conditions less frequently. Intra-annual (within a year) variation in flows is important to organisms that respond to the seasonal peaks and lows of natural flow regimes for spawning or migratory behaviors. Scientists making instream flow recommendations must be aware of temporal considerations and incorporate interannual flow variability on an appropriate scale. For example, the life history of a long-lived (decades) species such as paddlefish is different from that of certain minnows, which may live, reproduce, and die in two or less years. These considerations dictate that temporal aspects of instream flow management differ between groups of organisms. Furthermore, habitat requirements of species may shift seasonally and diurnally, and they may also differ by sex or life stage.

3.2.2

Hydrology and Hydraulics

Hydrology refers to the flow of water and has four dimensions: lateral (channel-floodplain interactions), longitudinal (headwater to mouth), vertical (channel-groundwater interactions), and temporal aspects including inter- and intra-annual variation. Characteristics of hydrology that define the flow regime include the magnitude, duration, timing, frequency, and rate of change.

Following the recommendation of the National Research Council (2005), the Texas Instream Flow Program will identify a set of four components of a flow regime intended to support a sound ecological environment. These components are subsistence flows, base flows, high flow pulses, and overbank flows. Subsistence flows are low flows maintained during times of drought. Base flows represent the range of "average" or "normal" flow conditions in the absence of significant precipitation or runoff events. High flow pulses are short duration, high magnitude (but still within channel) flow events that occur during or immediately following storm events. Overbank flows are infrequent, high magnitude flow events that exceed channel banks and enter the floodplain. (Further descriptions of these flows are provided in Section 6.1.) Additional flow components may be necessary for some sub-basins.

Hydrologic time series are an important tool for assessing potential impacts to riverine ecosystems. Daily time steps or shorter intervals may be needed to address biological processes such as habitat use and spawning. For example, flows downstream from hydropower facilities may vary profoundly on an hourly basis, which may be important in assessing habitat availability and use. When considering dissolved oxygen, whose concentrations vary diurnally, an hourly or other sub-daily step may be required. Larger time steps (months, years) are more suitable for addressing physical processes such as creating and maintaining habitats. Hydrologic time series can be developed to reflect natural, historical, and proposed flow conditions. Developing these time series will allow comprehensive assessment of potential impacts to fish and wildlife resources.

In a basin-level assessment, the hydrologic network (geography of flows) is important to understand. Watershed contributions, water right diversions, reservoir operations, return flows, and lateral and vertical exchanges are some of the factors that should be described in multiple spatial and temporal scales.

Hydraulics refers to the distribution of water velocities and depths resulting from the channel morphology and discharge through the channel. Since many aquatic organisms prefer particular combinations of velocities and depths, hydraulic conditions are important for describing instream habitat. A hydraulic model can be used to describe how velocities and depths change with changing flow. In fact, a major effect of hydrologic alteration is a change in the hydraulics that directly influence habitat.

3.2.3

Water Quality

Water quality parameters, including temperature, dissolved oxygen, pH, conductivity, turbidity (fine sediment), and other parameters, are important to growth, survival, and reproduction of aquatic organisms. Water quality characteristics reflect watershed geology, land use, climate, and sources of organic matter and nutrients. Because stream fishes and macroinvertebrates are cold-blooded, water temperature has a significant influence on their growth (metabolic rate), survival (lethal temperatures), and reproduction (spawning cues and egg incubation) (Armour, 1991). Temperature ranges tolerated by organisms vary by taxa and life-stage. Factors that influence temperature include flow, channel width in combination with riparian shading, thermal inputs, turbulence, and current velocity. In addition to the importance of temperature, dissolved oxygen also influences survival and distribution of lotic biota as mentioned previously in Section 3.2.1. Streamflow, water temperature, turbulence, organic matter decomposition, algal and macrophyte photosynthesis and respiration, and animal respiration all influence dissolved oxygen concentrations in lotic systems. Turbidity, conductivity, pH, and other factors may constrain or limit the distribution and abundance of aquatic biota.

3.2.4

Geomorphology

Geomorphology considers the physical processes that form and maintain stream channels and habitats, flush fine sediments, and transport sediment loads. In combination with the characteristics of the available sediment supply, the balance of flow magnitude and frequency acts to form the physical characteristics of a river or stream. As a result, geomorphic processes vary between and within basins and sub-basins. For example, geomorphic processes occur over a range of flows, but stream power, the energy available for sediment transport processes, increases with discharge. As a result, individual, large-magnitude flow events have a greater immediate effect on the physical features of a river system than individual, small-magnitude events. However, in many basins or sub-basins, large-magnitude flow events occur infrequently, such as once a year or once every few years. Over a period of several years, the overall effect of large-magnitude events may be less than the combined effect of moderate flow events that occur many times during that same time period. The relative geomorphic importance of large-, moderate-, and small-magnitude flow events will vary between basins and sub-basins.

Individual flow components play different roles in maintaining the physical features of a river system. High flow pulses play an important role in developing and maintaining in-channel habitats. Although smaller in magnitude than overbank flows, high flow pulses occur more frequently and, therefore, play a more active role in sculpting in-channel habitats. In contrast, overbank flows play a critical role in developing and maintaining riparian areas and floodplain habitats. The duration, rate of increase and decrease, and sequence of flow events also influence physical processes and may have important biological consequences. For example, as flow recedes after a large flow event, fine sediments may accumulate within in-channel habitats. This may reduce the suitability of the habitat for spawning, foraging, or refuge for some species (Milhouse, 1998).

Changes in the hydrologic regime influence geomorphic processes by altering the magnitude, duration, and frequency of flow events that transport sediment. Geomorphic processes are also altered by disturbances to the sediment regime, such as trapping coarse sediments in reservoirs or land use changes. When either the hydrologic or sediment regime is altered, an understanding of geomorphic processes is required to evaluate potential consequences to the physical features of a river.

3.3

CONNECTIVITY, DIMENSION, AND SCALE IN STREAM SYSTEMS

Connectivity, dimension, and scale are important considerations in developing and executing many aspects of sub-basin studies, including the development of conceptual models, design of technical evaluations to ensure spatial scales are commensurate among the disciplines, and integration of study results (NRC, 2005).

The physical, chemical, and biological processes that facilitate ecosystem function define the boundaries of a stream or river ecosystem. Those boundaries may not be readily apparent if one considers the broad possibilities for connectivity beyond the apparent channel or study reach to areas that include upstream and downstream river reaches, tributaries, the surrounding floodplain, and groundwater, among others. Adding to the complexity is that processes influenced by connectivity may operate at different spatial and temporal scales. The riverine ecosystem includes not only the water and habitat in the channel, but also encompasses these broader connections.

Connectivity refers to the movement and exchange of water, nutrients, sediments, organic matter, and organisms within the riverine ecosystem. Connectivity is complex, encompassing physical, hydrological, chemical, and biological processes. It occurs laterally, longitudinally, vertically, and temporally. Lateral connectivity between the floodplain and the river channel is important to maintenance and function of riparian areas and unique floodplain features, such as oxbow lakes. Longitudinal connectivity is important for transporting and processing nutrients and organic matter, migratory species, and physical processes (such as sediment transport). Water quality characteristics also show a strong longitudinal dynamic. Vertical connectivity is important biologically since the hyporheic zone—the zone under a river or stream comprising substrate whose interstices are filled with water—may support tremendous populations of macroinvertebrates. Vertical connections also exist between the stream channel and aquifers; some lotic systems recharge aquifers, and base flows in others may be supported by spring flows and seeps. Temporal aspects are related to the timing of events that mediate connectivity (such as overbank flows that connect instream processes with floodplains) and the life history of aquatic and riparian species.

In addition to connectivity, dimension of stream segments is an important consideration in developing sub-basin studies. The longitudinal dimension of streams refers to processes that operate from headwaters to mouth. The river continuum concept describes natural changes in physical gradients and biological attributes facilitated by the unidirectional flow of water and matter (Vannote and others, 1980). Many studies have been conducted to test or complement the river continuum predictions. For example, the nutrient spiraling concept states that nutrients have open cycles, or spirals, because of the dynamics of flow (Newbold and others, 1981; Elwood and others, 1983). The length of a given spiral is a function of transport rate, physical retention, and biological uptake. Stazner and Higler (1986) developed the stream hydraulics concept to explain biological zonation in the longitudinal dimension as related to clear changes in hydraulic conditions.

Studies have also expanded the concept into lateral and vertical dimensions. The flood pulse concept describes the process by which matter (nutrients, sediments, and biota) is regularly exchanged between the river and the floodplain (Junk and others, 1989). The ecological characteristics and productivity of both the river and the floodplain are linked and influenced by the frequency and duration of overbanking events. The hyporheic corridor concept recognizes the importance of subsurface-surface interactions, thus, addressing the vertical and lateral dimensions (Stanford and Ward, 1993).

Physical, hydrological, chemical, and

biological processes reflect temporal aspects of ecosystem function. Water quality may change both diurnally and seasonally. For example, dissolved oxygen in streams may decrease at night because of plant and algae respiration and during summer months when stream waters are warmer. Streamflows also vary seasonally, reflecting the seasonal patterns in precipitation and evaporation, as well as human influences from diversion and pumping. Flows can also vary over longer time periods (several years to decades) reflecting the cyclic patterns of drought and flood experienced in Texas. As a result of the hydrologic dynamics, changes in hydraulics and geomorphology influence habitat dynamics and, thus, biological processes.

Human influences have the potential to affect instream resources through these connections and linkages. For instance, alterations to landscapes through urbanization and floodplain development may have substantial effects on instream processes even when miles away from the area of interest. Similarly, water development projects and their associated changes in flow regimes influence connectivity. Impoundments trap sediment and disrupt habitat-forming physical processes, alter thermal and nutrient regimes, modify dissolved oxygen regimes and turbidity, and block migratory passages for aquatic organisms (Collier and others, 2000). Reduced high flow pulses and overbank flows alter the connectivity between floodplains, riparian areas, and the river channel, affecting the lateral exchange of nutrients, organic matter, sediment, and biota (Nilsson and Svedmark, 2002). Groundwater pumping can also have an effect by reducing levels in aquifers that may provide base flow to streams. At a smaller scale, water diversions can reduce flow, making shallow, erosional habitats unsuitable, and also affect longitudinal connectivity by inhibiting upstream migration by some aquatic organisms.

Processes that influence instream and riparian habitat operate at multiple scales, making the recognition of those scaling issues particularly important in assessing instream flow requirements (Poff, 1997; Fausch and others, 2002). Relevant scales for lotic species of fish and invertebrates can include microhabitat, channel unit or mesohabitat, stream reach, and basin or watershed (Poff, 1997). For example, at the microhabitat scale many flow-dependent species demonstrate preferences for faster current. At the mesohabitat scale, riffle-dwelling species use riffles almost exclusively although others may use them only at night. At the reach scale, riparian conditions may influence trophic structure (the presence of sufficient particulate organic matter input, such as leaf matter, to facilitate a shredder-dominated macroinvertebrate community). At the basin or watershed scale, barriers to migration may render some habitats unavailable at all times. Consequently, the scale of resource issues must be incorporated into the study design, selection of models and tools, and integration of study results.

Researchers have published many nomenclatures describing the spatial scale of riverine ecosystems (Frissell and others, 1986; Imhof and others, 1996; Harby and others, 2004; Brierley and Fryirs, 2005). Unfortunately, there has been little standardization of terminology, which may contribute to confusion during multidisciplinary studies (Benda, 2002). In order to ensure the consideration of appropriate spatial scales and improve communication among disciplines, the Agencies have agreed on a common nomenclature for riverine spatial scale during sub-basin instream flow studies (Figure 3-1). The nomenclature of Frissell and others (1986) is from the perspective of fisheries biology and is adapted for small streams in the Pacific Northwest. This accounts for the relatively small overall spatial extent of units. In contrast, the units of Imhoff and others (1996) are adapted for larger river systems and include explicit recognition of the effect of the watershed on river processes at larger scales. Harby and others (2004) reflect a habitat modeling perspective. Their nomenclature also includes a unit called "picohabitat" (not shown in Figure 3-1) whose dimension is on the order of centimeters. Brierley and Fryirs (2005) reflect the perspective of fluvial geomorphology.

Individual disciplines may continue to use discipline-specific nomenclature during sub-basin studies, but terms will be related to the common nomenclature. For example, geomorphic studies may still be conducted with a focus on "landscape units" and their effect on geomorphic processes. If used in communication with other program staff, this unit designation will be defined by its common nomenclature (Figure 3-1).

Definitions of spatial scale units adopted by the Texas Instream Flow Program are as follows:

a. **Sub-basin**—the full geographic scope of priority studies within major river basins in Texas, including the main channel, floodplain, tributaries, and contributing watershed area of all study segments.
b. **Segment**—subset of sub-basin study area. For priority studies, segments are equated to the corresponding river segments described in 30 Texas Administrative Code §307.1 through 307.10. The Agencies recognize that significant processes at this scale extend beyond the channel and include tributaries and contributing watershed area.
c. **Reach**—subdivision of a segment that exhibits relatively homogeneous channel and floodplain conditions (hydrology/hydraulics, biology, geomorphology, and water quality) bounded by breaks such as

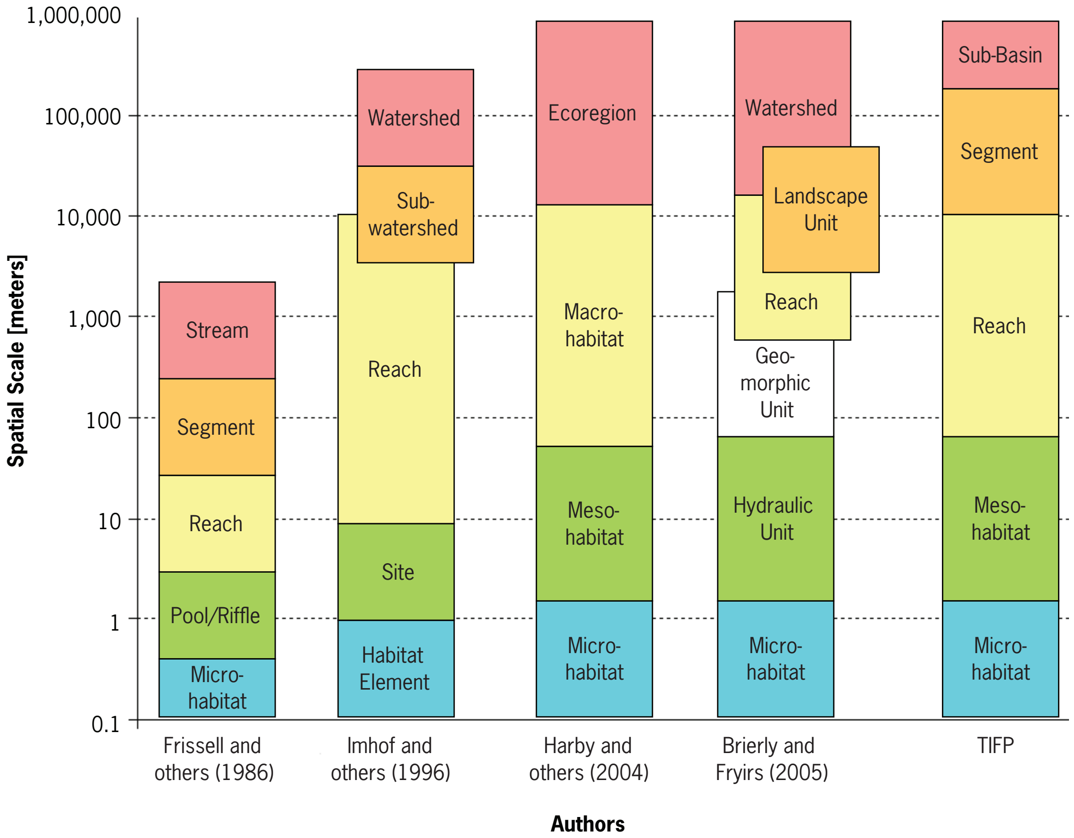


Figure 3-1. Nomenclatures describing the spatial scale of riverine ecosystems.
TIFP=Texas Instream Flow Program

the confluence of major tributaries and significant geomorphic features. The number of reaches within a segment depends on the degree of heterogeneity.

d. **Mesohabitat**—basic structural elements of a river or stream from an ecological perspective. For alluvial rivers, these elements include scour pools and submerged transverse bars (Trush and others, 2000). For smaller streams, mesohabitats are known by such names as pool, riffle, run, and chute.

e. **Microhabitat**—zones of similar physical characteristics within a mesohabitat unit. Differentiated by aspects such as substrate type, water velocity, and water depth.

4 *Peer Review and Stakeholder Input*

Although the Agencies have statutory responsibility to carry out the Texas Instream Flow Program, they seek collaboration with the public on the execution of instream flow studies. This collaboration is crucial to building support for the goals and objectives of the program and ensuring that local knowledge and values are incorporated in the studies. Meaningful participation in the process increases public confidence in both the science employed by and recommendations resulting from instream flow studies. In order to cultivate public confidence, the Agencies are committed to program transparency, stakeholder participation, and scientific peer review. Public documents will describe the approach and methods of the program. For all sub-basin studies, the Agencies will make available to the public final study designs, reports, and supporting documents. These will be posted on the Texas Instream Flow Program Web site: www.twdb.state.tx.us/instreamflows/index.html

The Agencies are dedicated to implementing a process in which stakeholders may provide input and have the opportunity to participate in the instream flow studies. The Agencies also seek stakeholder technical and/or financial participation in performing the studies, which can maximize resources and assist in meeting statutory deadlines. Additionally, the program was designed so that instream flow studies could be conducted by qualified third parties with the Agencies' oversight.

Finally, although implementation is beyond the scope of the Texas Instream Flow Program, the Agencies envision that participating stakeholders may be involved in implementing instream flow recommendations through the Senate Bill 3 process established by the 80th Texas Legislature or other regulatory proceedings. They may also be involved in developing future monitoring and adaptive management strategies.

4.1
STAKEHOLDER PROCESS

Stakeholder participation is critically important to maintaining the transparency and credibility of instream flow studies. The Agencies have chosen to commit substantial time and resources to developing a public- and peer-reviewed study methodology and a process to integrate stakeholders into the instream flow program.

The Texas Legislature has charged the Agencies with the ultimate responsibility for instream flow studies and data collection. Texas Water Code §16.059(a) provides that

> the Parks and Wildlife Department, the commission, and the board, in cooperation with other appropriate governmental agencies, shall jointly establish and continuously maintain an instream flow data collection and evaluation program and shall 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.

The legislature also imposed a deadline of December 31, 2016[1], for the Agencies to complete priority studies.

The stakeholder process will offer the opportunity to work with the Agencies throughout the course of individual studies through a sub-basin specific work-

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[1] The original deadline in Senate Bill 2 called for completion of priority studies by December 31, 2010. Senate Bill 3 extended the deadline to 2016.

group with broad representation. Likely parties include, but are not limited to, public agencies, regional water planning groups, river authorities, groundwater conservation districts, municipalities, industries, agricultural interests, commercial and sport fishing interests, recreational interests, environmental groups, public interest organizations, and academic institutions. The Agencies will seek input and participation on both technical and nontechnical issues. During this process, the Agencies will ensure consistency with statewide goals as well as with state and federal legislation and policies. We will seek stakeholder involvement in each step of the instream flow study process (Figure 4-1).

The Texas Instream Flow Program stakeholder process includes these primary goals:

- Obtain information from stakeholders that will allow the Agencies and others to understand local concerns and perspectives.
- Engage stakeholders in study design development.
- Encourage stakeholders to commit meaningful time and resources to developing and performing the sub-basin studies.
- Obtain comments from stakeholders on study results.
- Build trust in the underlying science and performance of the sub-basin studies so that study results are considered valid, credible, and usable by the Agencies and other interested parties.

To meet these goals, stakeholders will be engaged in the process of developing goals and study designs for specific sub-basin instream flow studies. The National Research Council (2005) noted that stakeholder involvement in goal setting is particularly important given the potential for conflict among water users. We also recognize that stakeholders will bring valuable knowledge of Texas rivers to the table. Six stages in the stakeholder process are described below.

STAGE 1:
Identify and Engage Stakeholders

Because the success of the stakeholder process depends on garnering local participation and support, the Agencies will rely on local resources to publicize and communicate information about the sub-basin study. We will notify stakeholders of sub-basin orientation meetings through existing, locally oriented means of communication, such as civic groups, local entities, newsletters, press releases to newspapers, or other local outlets that could disseminate information about initial meetings. Examples of entities that may reach people likely to be interested in participating include chambers of commerce, libraries, schools, volunteer organizations, trade groups, Clean Rivers Program steering committees, and environmental groups. Media outlets such as local newspapers, radio, television, and the Internet may also be used.

Because they are local organizations that already have working stakeholder groups established for the Clean Rivers and other basin-specific programs, river authorities may be effective at disseminating information to stakeholders. They can send meeting announcements and information to groups or individuals who have shown interest in their work. The Agencies may contract with local river authorities or other local resources to assist in identifying stakeholders, distributing information, and arranging meetings at local sites. Although a river authority may also serve as a stakeholder, its input will be considered at the same level and manner as input received from other stakeholders.

Finally, the Agencies will offer alternate opportunities for participation, such as submitting online and email comments, to ensure that all stakeholders, regardless of meeting attendance, have the opportunity to provide input.

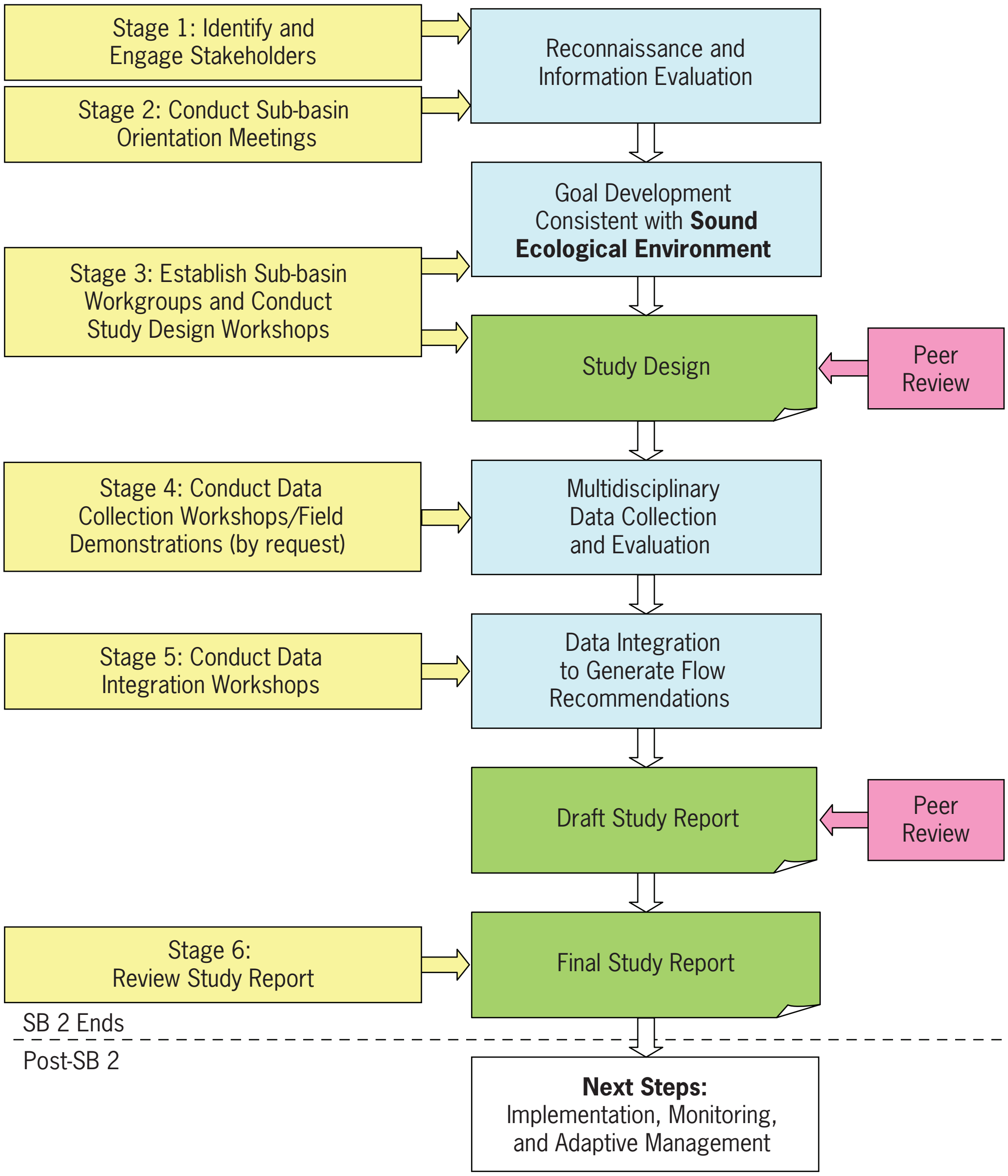


Figure 4-1. Stages of stakeholder participation in sub-basin specific studies of the Texas Instream Flow Program.

STAGE 2:
Conduct Sub-basin Orientation Meetings

After notifying potential stakeholders through local sources, we will hold an initial stakeholder orientation meeting(s) to query local residents about their historic and current perspectives of the sub-basins as well as to identify important concerns. Stakeholders will be asked to give ideas about what they would like to see as a result of the studies. Orientation meetings may be held outside of regular business hours to allow for broader attendance and participation.

At the orientation meeting, the Agencies will specifically

- educate stakeholders about the purpose of the studies and how the data will be used;
- describe the role of stakeholders in the process;
- seek involvement from stakeholders to participate in the study process;
- obtain stakeholder input that can be

used in instream flow studies; and
- discuss the relationship between science and policy and explain to stakeholders that at some point different parties will make choices regarding what to do with the study results according to current legislation, mandates, and policies.

An important component of the orientation meeting will be for the Agencies to invite stakeholders to serve, along with Agency staff, on sub-basin workgroups whose purpose will be to develop the study design. Workgroups will be established with the intent of bringing to the table key stakeholders who will provide a diverse representation of the issues so that all perspectives can be considered. We will establish an email list to actively notify stakeholders, regardless of whether or not they continue on as sub-basin workgroup members, about the progress of the process and give them the opportunity to provide additional input as the studies progress.

STAGE 3:
Establish Sub-basin Workgroups and Conduct Study Design Workshops

Stakeholders who express an interest in participating in the sub-basin workgroups will be notified of a series of workshops in which they will be asked to participate in the process of designing the study. At these workshops, sub-basin workgroup participants will assist in

- applying the definition of “sound ecological environment” (as described in Section 5.2) to the sub-basin or segment;
- identifying specific study areas within the sub-basin;
- determining study goals and objectives; and
- developing a draft time frame for the design and performance of the study, recognizing all statutory and practical resource limitations.

STAGE 4:
Conduct Data Collection Workshops/Field Demonstrations (by request)

At the request of sub-basin workgroups, members will be invited to attend sub-basin study and data collection workshops/field demonstrations so that they can better understand field techniques and constraints.

STAGE 5:
Conduct Data Integration Workshops

Sub-basin workshops will be held at the conclusion of the field studies. At these workshops, the Agencies will outline and explain the data and garner workgroup input on the methods used to integrate data and generate instream flow recommendations. As the Agencies draft the study report, we will consider comments from the sub-basin workgroup.

STAGE 6:
Review Study Report

In the interest of efficiency and consistency with statewide goals, sound scientific principles, and state and federal legislation and policies, the Agencies will take the lead in developing the study report. However, the report will be provided to stakeholders for review and comment before it is finalized. The Agencies will consider all comments before finalizing the report. All feedback received from stakeholders will be published, along with responses from the Agencies.

4.2
PEER REVIEW

Scientific peer review is recognized as an important part of an instream flow assessment program (Arthington and others, 1998; NRC, 2005). In order to ensure public trust in the science behind instream flow recommendations, the activities of the Texas Instream Flow Program will be peer reviewed. The National Research Council (2005) recommended “scientists not working directly on the studies” review the sampling methodologies, results of the individual technical studies, and the progress of the overall instream flow program. Results of these reviews should then be communicated to the "involved scientists, instream flow scientific community at large, and stakeholders" and be assessed through "an independent, interdisciplinary, periodic peer review process" (NRC, 2005).

The Agencies intend to establish a peer review team consisting of independent experts in the fields of biology, hydrology and hydraulics, water quality, and geomorphology (physical processes). This peer review team will review all sub-basin study designs and reports. In addition to the peer review team, the Agencies may bring in experts from other disciplines to assist in particular situations. The diversity of sub-basin studies will require varied approaches in conducting the instream flow studies, and the Agencies must ensure that models and methods are applied appropriately. Peer review will provide critical input for improving the technical soundness of products and recommendations and will also increase public trust by ensuring that sound science is at the foundation of these studies.

In addition, research findings related to instream flow assessments will be submitted for publication in peer-reviewed journals. The Agencies submitted the original version of this document for peer review by national experts (NRC, 2005). Incorporating scientific peer review of the instream flow program is intended to increase public trust and improve the technical soundness of products and recommendations.

5 *Study Design*

Sub-basin study designs will necessarily flow from the statewide goals and objectives of the Texas Instream Flow Program as outlined by Senate Bill 2 and tackle the specific issues associated with a defined study area. The evolution of this approach begins with the overall legislative directive and narrows down to a specific sub-basin in question (Table 5-1). Key to developing a consistent approach for the studies across basins is ensuring that the goal statements for a specific geographical area are consistent with the statewide goal of supporting a sound ecological environment. Goals, as opposed to objectives, should be general statements about desired outcomes (for example, conservation of paddlefish populations). Once the study goals are identified, objectives should be established that represent the specific means of achieving those study goals.

A variety of tasks critical to establishing sub-basin study goals and objectives will form the foundation of a suitable study design. The study design will include a summary of available data and reconnaissance surveys; conceptual models of the river system; goals, objectives, and indicators for the study; and descriptions of the proposed study sites, methods, and tools. In the reconnaissance and information evaluation phase, the Agencies will identify cooperators and stakeholders and assemble available data with their assistance. After preliminary analysis of that data, field surveys will be conducted to address data needs. Following that process and in cooperation with stakeholders and cooperators, primary issues related to the study will be defined along with statements of goals and objectives. The Agencies will also guide the selection of appropriate indicators and complete a draft study design. The draft study design will be submitted for both scientific peer review and stakeholder comment, with subsequent revisions to be made as necessary.

5.1
RECONNAISSANCE AND INFORMATION EVALUATION

Prior to initiating program efforts, the Agencies will identify the geographic scope of the study. Study areas will consist of sub-basins (portions of a major river basin) composed of multiple Texas Commission on Environmental Quality designated stream segments (30 Texas Administrative Code, §307.10[1] Appendix A). Study areas will extend from the river channel to the riparian and floodplain area of the segments and consider tributaries, floodplain areas, groundwater interactions, and watershed areas.

The Agencies will assemble and evaluate previously collected data for the study area to determine what historic conditions may have been like, assess the current understanding of the system, and identify knowledge gaps and areas where additional data should be collected. This step provides a preliminary understanding of the river ecosystem and any issues of acute and/or historical concern.

Once knowledge gaps are identified, the Agencies will undertake preliminary data collection and reconnaissance efforts focused on familiarizing agency personnel with the study area and current condition of the river ecosystem. Access points and potential study sites will be located. Data collection will focus on filling in gaps in the available data and establishing the current condition of the system.

After completing a preliminary analysis of historical and reconnaissance data, the Agencies will summarize findings, including geographic information system (GIS) data layers and conceptual models

Table 5-1. Summary of development of sub-basin study design from statewide goals and objectives.

Legislative Directive:
"…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."

Statewide Goal: Sound Ecological Environment
A resilient, functioning ecosystem characterized by intact, natural processes and a balanced, integrated, and adaptive community of organisms comparable to that of the natural habitat of a region.

Statewide Objectives: To Meet the Criterion of "Sound"

- Evaluate intact natural processes:
  - Characterize system hydrology and hydraulics
  - Examine status of geomorphic processes within the system
  - Characterize system water quality
  - Define connectivity issues within the system
- Evaluate biological communities:
  - Examine the integrity of the biological community
  - Examine biodiversity within the system
  - Define the influence and relationship of other riverine components relative to biology of system

Study Goals:
Develop goal statements for the specific sub-basin and relate them to the statewide goal. Primary focus would be to apply the definition of sound ecological environment relative to the specific sub-basin. These goals should be general statements about desired outcomes, allowing cooperators and stakeholders to grasp the intent of the study (for example, to ensure conservation of riparian areas in the Sulphur Basin).

Study Objectives:
Objectives should be established that are the specific means of accomplishing the stated sub-basin goals. (For the example goal above: provide sufficient timing and frequency of overbank flows to conserve hardwood bottomlands.)

Tasks Necessary to Develop Sub-basin Goals and Objectives:

- Identify cooperators and stakeholders
- Define distinct geographical scope of study area
- Assemble existing information and determine reconnaissance needs
- Use field surveys to develop additional baseline data and address data gaps
- Develop a conceptual model of the system in question using existing and reconnaissance information
- Define primary issues affecting instream flows
- Establish goals and specific objectives

Indicators and Study Design:
Well-defined objectives will lead naturally to the selection of indicators, which are measurable factors representing the disciplines of hydrology, geomorphology, water quality, or biology and are responsive to variations in flow. Addressing some objectives will require using multiple indicators from each of the disciplines. (For the example goal above: conserving hardwood bottomlands may require indicators related to soil moisture, frequency of overbank flows, and influx of sediment and nutrients.) Once important indicators have been selected, a specific study design with procedures and means for implementation can be developed.

describing the relationship between flow regimes and ecological health. The summary will provide the best description available of the current condition of the river system. If data are available, we will estimate historical conditions for the river, as well as compile a comprehensive list of stressors.

5.1.1

Compile, Review, and Georeference Available Studies and Data

All available data and study reports related to the hydrologic, biologic, geomorphic, water quality, and connectivity of the study area will be assembled. Given the interdisciplinary nature of instream flow studies, relevant data span several academic disciplines. Various public agencies, private consultants, academic researchers, and others have collected a substantial amount of data on various aspects of stream ecology for most Texas rivers. The primary objective of this task is to compile and organize previously collected information on the hydrology, biology, physical habitat, and water quality of the proposed study area. This approach was employed for the Guadalupe (Longley and others, 1997) and Trinity rivers (Kiesling and Flowers, 2002). The Trinity River report also included a GIS tool with spatial coverages and attribute tables for the various data sets.

Many federal programs related to natural resources will be valuable sources of information for sub-basin studies. Agencies with such programs include the U.S. Geological Survey, U.S. Army Corps of Engineers, U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency, Natural Resources Conservation Service, and National Oceanic and Atmospheric Administration.

The U.S. Geological Survey is the primary federal agency responsible for collecting, monitoring, and analyzing natural resources data. In cooperation with the Texas Water Development Board and other local partners, the Survey maintains a network of surface water flow gages within Texas. This network provides invaluable flow data for hydrologic studies. In order to develop rating curves for gage locations, the Survey collects channel cross-sectional data that may also prove useful for geomorphic investigations (Juracek, 2000). In addition, they periodically collect water quality and sediment data at some gage sites and have completed studies on water quality and quantity issues. The Survey is also a source of aerial photography and digital elevation and topographic maps.

The U.S. Army Corps of Engineers provides engineering services to the nation, including water resources and other civil works projects. They serve as the national regulatory authority for wetland issues (Section 404 of the U.S. Clean Water Act) and cooperate with local entities on flood control and aquatic restoration projects. The Corps of Engineers conducts hydrologic and hydraulic modeling in support of the National Flood Insurance Program administered by the Federal Emergency Management Agency. They provide information that includes studies and data related to dams, operation of reservoirs, restoration projects, and flood studies on specific river segments.

The U.S. Fish and Wildlife Service is the national agency charged with conserving, protecting, and enhancing fish, wildlife, plants, and habitats. They have conducted studies related to specific species and locations in Texas, and they also compile information on best management practices related to invasive species, habitat restoration, and wetland preservation.

The Natural Resources Conservation Service provides technical assistance to landowners, communities, state and local governments, and other federal agencies to help them conserve soil, water, and other natural resources. The Conservation Service is a source of aerial photography, including soils maps and surveys, and information related to sediment processes.

Responsibilities of the National Oceanic and Atmospheric Administration include maintaining and improving marine and coastal ecosystems, delivering weather, climate, and water information, and understanding the science and consequences of climate change. The organization is a source of weather, Landsat, and other data.

The Agencies have also gathered considerable data relative to riverine ecosystems in Texas. For example, the Texas Water Development Board has conducted planning studies related to instream flow requirements downstream of proposed water supply reservoirs. Through research and planning funds, the agency has also contracted with universities and other entities to conduct research and collect data of direct interest to instream flow studies. The Texas Natural Resources Information System, a division of the Texas Water Development Board, is the state's clearinghouse for maps, aerial photos, and digital natural resources data. The Texas Parks and Wildlife Department has completed studies related to riparian and aquatic species, as well as completing or cooperating on instream flow studies. The Texas Commission on Environmental Quality administers the water right permitting process that includes hydrologic and ecological analyses associated with requests to impound and divert water. The Commission also administers the Texas Clean Rivers Program and state and federal water quality permit programs, both of which provide water quality monitoring data and modeling studies for all major rivers in Texas.

Other state agencies also have data of interest to instream flow studies. For example, the Texas Department of Transportation has data related to channel cross sections and test bores at bridge construction sites. When available, such data can be used to evaluate long-term river channel adjustments (Phillips and others, 2005). The Texas General Land Office is a source of historical maps.

All major river basins in Texas have one or more regional water resource management agencies, usually a river authority. These authorities, most of which were created by the state as conservation and reclamation districts in the 1930s, have unique statutory responsibilities outlined in their respective enabling legislations. Local river authorities are the Texas Commission on Environmental Quality's primary partners in the Clean Rivers Program and engage in monitoring that may include flow gaging, water quality monitoring, biological sampling, and weather data collection. They also have local knowledge of river conditions and behavior, both current and historical, have frequent contacts with stakeholders in their basins, and are aware of activities and issues related to the river systems they manage.

Many academic institutions in Texas maintain active research programs related to various aspects of stream ecology, engineering, and water resource management. These include the University of Texas, Texas A&M University, Texas State University, Texas Christian University, Baylor University, and others. Information available from these sources includes research reports, publications, monitoring data, theses and dissertations, museum records, and other data related to specific rivers and streams.

Engineering and consulting companies and private organizations may be an additional source of information. For example, The Nature Conservancy of Texas collects and maintains information related to rare, endemic, and invasive species statewide. Private organizations like the Caddo Lake Institute provide data, technical reports, and documents related to specific river segments or locations in Texas.

During the reconnaissance and information evaluation step of an instream flow study, to the extent possible, all available data related to a study area will be incorporated into GIS, showing the type of data collected, location and timing of collection, and entity collecting the data. Available data for a study area will be reviewed and evaluated. Data collection methods will be assessed to determine each data set's quality and comparability to other data sets. Available studies and data will be summarized for each study area.

5.1.2

Conduct Preliminary Field Surveys and Analyses

After reviewing the available data, preliminary field surveys and analyses will be conducted to fill in data necessary for describing the current condition of the river ecosystem, confirming issues and concerns suggested by initial analyses, and identifying sites suitable for intensive technical studies. Initial field efforts will involve air, land, and water level reconnaissance, as appropriate, to identify potential representative reaches, study sites, human impacts, and extant fish and wildlife resources.

Aerial Surveys: During the aerial survey, notes and photographs will be taken related to potential access points, instream habitat features, and floodplain characteristics (such as the presence of oxbow lakes, width of riparian corridor, nature of human activity). This will provide a general overview of the study area in a time-efficient manner. Aerial surveys should be performed when flows are at or less than the median value and habitat features are relatively easy to identify.

Land Surveys: Access points for launching boats, locations for remote sensors, and survey points will be visited before making final determinations on study site and boundaries. Preliminary assessment of riparian and floodplain areas will also be made.

Boat Surveys: Longitudinal surface surveys will be performed for each study area for either the entire study area or representative reaches. During the survey, areas with different mesohabitat features, overhead cover, substrate, and instream cover, such as woody debris and boulders, will be delineated throughout the stream segment. Cross-sectional measurements will be taken at regular intervals along the channel. The longitudinal extent of mesohabitat types can be measured by logging the longitudinal position along the channel with Global Positioning System (GPS) instruments and coding the upper and lower boundaries of mesohabitats. These mesohabitat surveys will be performed when flows are at or less than the median value and habitat features are relatively easy to identify.

Preliminary field surveys and analysis will focus on establishing the current condition of the riverine ecosystem, investigating trends in condition obvious from field surveys or previously collected data, and selecting study sites for intensive technical studies. A more detailed description of technical activities is provided in Chapters 6 through 9. Activities in the four disciplines will include the following:

Hydrology: Analyze historic gage data to determine flow statistics representative of the hydrologic character of the study area. Identify historical and current features affecting hydrologic character, as well as potential future changes.

Biology: Identify species, habitats, and important issues and considerations within the study area. Species of interest will include those historically and currently present. Particular attention will be paid to key species (defined as those related to study objectives or that are particularly flow sensitive). Biota of interest may include plants, amphibians, birds, and mammals associated with floodplain and riparian areas, as well as in-channel resources, such as aquatic vegetation, invertebrates, mussels, and fish. Current and prior condition of stream and riparian biota will be assessed.

Geomorphology: Analyze previously collected data. Field surveys will focus on preliminary channel, bed form, and bank assessment and identification of active channel and floodplain processes. Evidence of changes in sediment regime and their causes will be documented. Geomorphic classification of the river segment will begin. Results may be constrained by limited data collected prior to these efforts and the short time frame available to observe large spatial and temporal scale processes.

Water Quality: Assess the water quality condition of the study area. Available data will be analyzed to identify trends, issues, and constituents of concern. Field surveys will supplement available data.

5.1.3

Develop Conceptual Models

Using the previously collected data and the results of reconnaissance surveys and preliminary analysis, a basic conceptual model of the study area will be developed. Such models provide a concise visualization of the current understanding of the riverine ecosystem. A conceptual model will also relate the components of the hydrologic regime with the technical components of the instream flow study (such as biology and water quality), thereby aiding in identifying relationships between flow regimes and the ecological health. Since several disciplines are involved in describing these relationships, the conceptual model will provide basic guidance on how disciplines must cooperate in order to complete technical studies and how components of the flow regime will be integrated. Conceptual models of riverine ecosystems are beneficial for developing study designs (CRCFE, 2001) because they provide

- clear articulation of how rivers function
- improved communication with the nonscientific community;
- visual description of current conditions, trends, and impacts of management actions;
- assistance in setting goals and objectives and prioritizing management actions;
- indication of additional research necessary to improve understanding;
- estimates of natural conditions for highly regulated systems;
- assistance in selecting appropriate indicators and assessment tools; and
- identification of key habitats and suitable sampling locations and study sites.

An example of a conceptual model for a portion of the Murray-Darling Basin (Australia) is provided in Figure 5-1.

5.2

GOAL DEVELOPMENT AND STUDY DESIGN

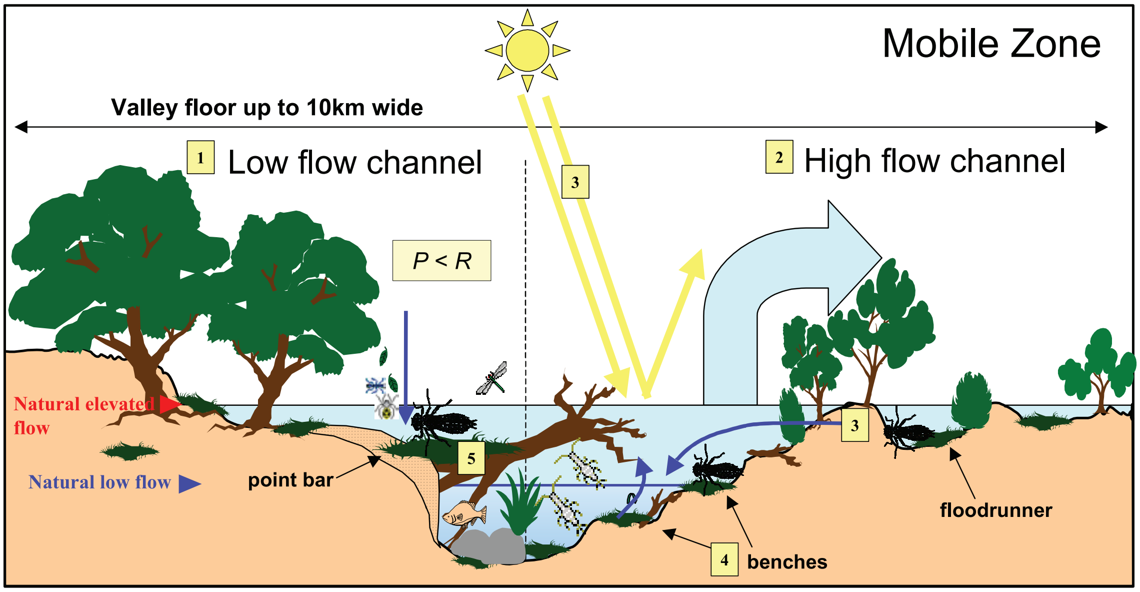
During the second step of a sub-basin instream flow study, stakeholders and the Agencies will collaborate to develop study goals that are consistent with statewide goals and objectives.

5.2.1

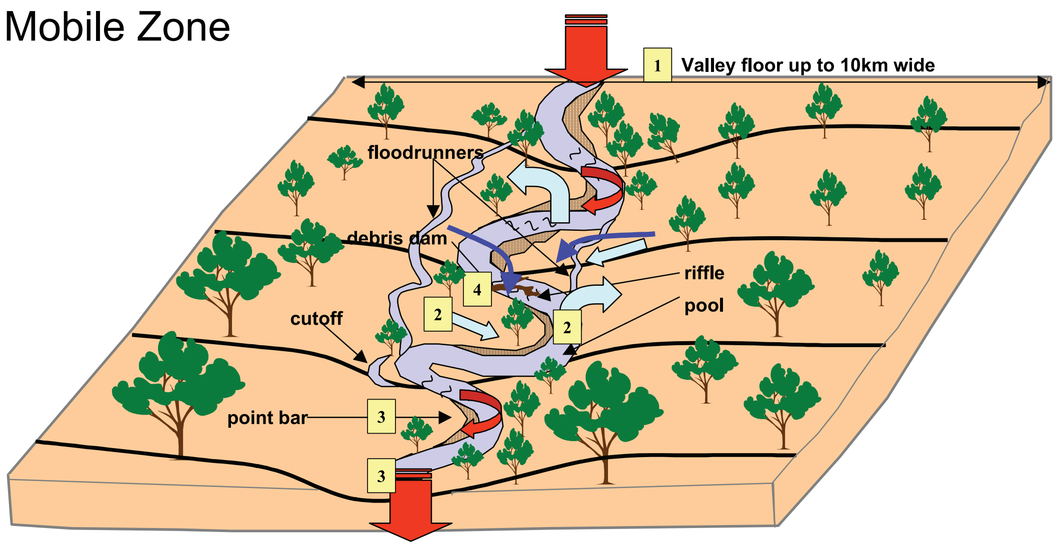
Develop Study Goals and Objectives

Together with stakeholders, the Agencies will review the statewide goals for instream flow projects and develop goals for the sub-basin instream flow study based on the desired condition of the river ecosystem. In essence, they will define what a sound ecological environment means for the specific study area. An example goal is the "vision of a healthy and productive River Murray" adopted in Australia (Text Box 5.1).

Once sub-basin goals are defined, objectives will be developed that describe what ecological outcomes would result from achieving study goals. For example, in Australia, the goal of "a healthy and productive River Murray" led to several objectives. One of these objectives was to reinstate ecologically significant elements of the flow regime. This objective was further defined to include reproducing some of the natural high, low, and zero flow behavior of the river, as well as flow variability, seasonality, and annual volume.



1 In the mobile zone high and low flow channel features are very distinctive. The low flow channel is characterized by large sandy point bars, riffles, and large, deep pool sections. In low flow, habitat is provided by cobble/gravel accumulations and riparian vegetation in riffle sections, fallen trees, detritus, and emergent vegetation in pool areas. 2 The high flowchannel is characterised by in-channel benches, flood runners, and complex floodplain features. In high flow, flooding of the terrestrial environment, in channel benches and floodrunners provide habitat in the form of fallen and inundated vegetation and detritus. 3 At high flow, detritus, sediments, and nutrients are flushed from the channel and the floodplain, which may temporarily increase turbidity and reduce light penetration. 4 Benches are important areas for storage of organic matter, nutrients, and sediments and play an important role in in-stream processes. 5 Fallen timber may create debris dams, trapping organic matter of various sizes, as well as providing food and habitat for invertebrates, fish, and frogs.



1 The mobile zone has a large valley floor, enabling development of floodplain features such as floodrunners, cutoffs and levees. 2 In high flows, lateral connections to the floodplain are established, and nutrients and detritus may be flushed into the main channel from the floodplain and in-channel benches, creating habitat and food resources for invertebrates, fish, and frogs. High flows also provide cues for fish migration, spawning, and dispersal. 3 The primary function of the mobile zone is transport of sediment and other material, with large storage areas such as point bars in the channel. 4 Detritus may also be stored in debris dams that can form in riffle areas from fallen timber.

Figure 5-1. Conceptual model developed for a portion of the Murray-Darling Basin, Australia (from CRCFE, 2001).

Text Box 5.1. Example of goals, objectives, indicators, and conceptual models for the Murray-Darling Basin, Australia.

The Murray-Darling Basin is one of Australia's largest drainage divisions, with just over 1 million square kilometers (386,000 square miles). The basin includes the three largest rivers in Australia—the Darling River at 2,740 kilometers (1,700 miles), the Murray at 2,530 kilometers (1,575 miles), and the Murrumbidgee at 1,690 kilometers (1,050 miles). In addition, the basin contains some 30,000 wetland areas. According to the Australian Department of Environment, Water, Heritage and the Arts (2008), at the time of European settlement, about 28 percent of Australia's mammal species, 48 percent of its birds, and 19 percent of its reptiles were found within the basin. Many of these species are now extinct or endangered. Over-allocation of water, increasing instream and dry land salinity, and impacts of global climatic change are recognized as threats to the long-term productivity and sustainability of the Murray-Darling Basin.

Conceptual models of the Murray-Darling Basin were developed for eight different geomorphic process zones (CRCFE, 2001). Zones included headwater pool, confined, armored, mobile, meandering, anabranching, distributary, and lowland confined zones. Geomorphic processes and the attendant biological and ecological processes vary from zone to zone. The conceptual model for the mobile zone is shown in Figure 5-1. Note that some of the terminology shown in this figure may be defined differently in Australia or be unique to Australia.

Collective efforts at all levels of government to restore the Murray to a healthy working river began in November 2003 (MDBC, 2005b). The national, state, and local governments involved in allocating the resources of the Murray-Darling Basin adopted the vision of a healthy and productive River Murray as their goal. In order to meet this goal, they agreed on the objectives summarized below:

1. Reinstate ecologically significant elements of the flow regime
2. Overcome barriers to migration of native fish species
3. Maintain current levels of channel stability
4. Protect and restore key habitat features in the river and riparian zone
5. Prevent the extinction of native species from the riverine system
6. Improve connectivity between the river and riparian zone
7. Manage flow-related water quality to sustain ecological processes and productive capacity (MDBC, 2005b)

Indicators related to these objectives are currently being developed. A number of indicators have been approved for basinwide application, including 13 indicators related to fish (MDBC, 2003a), 3 related to macroivertebrates (MDBC, 2003c), and 12 related to hydrology (MDBC, 2003b). Some indicators related to riparian and channel areas have been designated for specific regions. Water quality indicators are under development. Example indicators for each category are provided in Table 5.2.

5.2.2

Indicators

Sub-basin objectives lead quite naturally to the choice of indicators. See Text Box 5.2 and Table 5-3 for a description of how ecological indicators may be used for the Texas Instream Flow Program. Potential indicators include the entire realm of hydrological, biological, physical, and chemical indicators. For a sub-basin, a list of all practical indicators will be developed consistent with study goals and objectives identified by stakeholders for the study area. This list will then be pared down to ecologically significant indicators that are directly related to components of the flow regime. For example, in the Murray-Darling Basin of Australia, 12 hydrologic indicators were identified based on the objective of reinstating ecologically significant elements of the flow regime (Text Box 5.1). These included the number of high and low flow events, the magnitude of difference between annual flow maxima and minima, the timing of flow maxima and minima within the year, and annual flow volumes.

In developing program goals, the Agencies will consider the feasibility of goals given the current state of the river and constraints on system management. For example, large rivers in developed countries are highly impacted by development, and, thus, most riverine scientists agree that it is not feasible to attempt to return a river to pristine, natural conditions (Rutherford and others, 2000; Schofield and others, 2003). Instead, the goal for such rivers should be to improve their ecological condition. Palmer and others (2005) put it this way:

> The first step in river restoration should be articulation of a guiding image that describes the dynamic, ecologically healthy river that could exist at a given site. This image may be influenced by irrevocable changes to catchment hydrology and geomorphology, by permanent infrastructure on the floodplain and banks, or by introduced nonnative species that cannot be removed. Rather than attempt to recreate unachievable or even unknown historical conditions, we argue for a more pragmatic approach in which the restoration goal should be to move the river towards the least degraded and most ecologically dynamic state possible, given the regional context.

Using available data and conceptual models, the Agencies and stakeholders will collaborate to evaluate the range of conditions achievable and determine appropriate desired conditions for each specific river segment.

The Agencies will also provide input to stakeholders as objectives and indicators are developed and will assist stakeholders in choosing objectives that represent measurable progress toward goals. Selection of indicators will also consider current standards, methods, capabilities, and limitations of data collection equipment and techniques. Goals, objectives, and indicators will also conform to applicable federal and state law, including the federal Clean Water Act, Endangered Species Act, the Texas Administrative Code, Texas Water Code, and Texas Parks and Wildlife Code.

Goals, objectives, and indicators will consider existing programs, such as the Texas Commission on Environmental Quality's Water Quality Standards for designated and undesignated stream segments in Texas (30 Texas Administrative Code §307.10[1] Appendix A and Appendix D). For example, for the Lower Sabine River, the Commission has already established site-specific uses and criteria for designated segments (Table 5-4) and several smaller tributaries (Table 5-5). In addition, the aquatic life uses are based upon additional criteria related to the condition of the river ecosystem (Table 5-6). Although developed within the context of a water quality regulatory program, these criteria may be incorporated into goals, objectives, and indicators if they are relevant to identified instream flow issues.

Table 5-2. Example indicators for Murray-Darling Basin, Australia.

Category	Sub-category	Indicator	Comments/Description
Hydrology[a]	High flow	Number of 1 in 10 year floods	1 in 10 year annual return interval flood calculated for natural conditions.
	Low and zero flow	Number of low flow events	Low flow event defined as below the 90th exceedence percentile for natural conditions.
	Variability	Seasonal amplitude	Difference in flow magnitude between yearly high and low flows.
	Seasonality	Seasonal period index	Change in timing of annual high and low flow events from natural to current conditions.
	Flow volume	Median annual flow	Median of annual flow volumes.
		Mean annual flow	Mean of annual flow volumes.
Biology	Macro-invertebrate[b]	Richness	Biodiversity indicated by the number of taxa.
		Pollution sensitivity score	Observed families graded for sensitivity to pollution. The average of the grades is the score for the site.
	Fish[c]	Total species richness	Total species richness (native and alien) at each site compared to a predicted maximum species richness.
		Proportion native species	Proportion of fish species at each site that are native species.
		Proportion megacarnivores	Proportion of individual fish (native and alien) at each site that are megacarnivores (eat prey >15mm length).
	Riparian[d]	Waterbird breeding	Successful breeding in at least 3 years out of 10.
		Healthy vegetation area	55% of the Barmah-Millewa Forest in healthy condition.
Geomorphology[e]		Channel stability	Maintain current level of channel erosion.
Water Quality[f]		Total phosphorus	• Upland rivers: < 20 µg/L • Lowland rivers flowing to the coast: < 25 µg/L • Lowland rivers in the Murray-Darling Basin: < 50 µg/L • Lakes and reservoirs: < 10 µg/L • Estuaries: < 30 µg/L

Sources: [a]MDBC (2003b); [b]MDBC (2003c); [c]MDBC (2003a); [d]for the Barmah-Millewa Forest only, MDBC (2005a); [e]for the main channel of the River Murray only, MDBC (2005b); [f]NSWDEC (2008)

mm=millimeters

µg/L=micrograms per liter

Text Box 5.2. Use of ecological indicators in Texas Instream Flow Program sub-basin studies.

Ecological Indicators

Ecological indicators can be used to assess the condition of the environment. Ecological indicators selected to encompass the hydrologic, biologic, geomorphic, and water quality objectives set in consultation with stakeholders for a particular sub-basin will be monitored at spatial and temporal scales that reflect the processes relevant to establishing and maintaining a diverse and sustainable aquatic environment. Following the implementation of instream flow recommendations, long-term monitoring and assessing of the aquatic ecosystem using ecological indicators will ensue. These indicators will be used to measure progress toward achieving a sound ecological environment in a particular sub-basin. They will also be used to document the conditions, trends, processes, and phenomena associated with the aquatic ecosystem. Assessment of monitoring data will inform adaptive management decisions in the sub-basin.

Sub-basin indicators should be derived from a statewide suite of indicators modified for regional differences. The consistent use of a suite of indicators across Texas will aid in comparing ecological conditions. At the sub-basin level, these indicators will form a bridge between study goals and objectives and the goals of the instream flow program. Examples of ecological indicators relevant to aquatic ecosystems are presented in the table below.

Table 5-3. Example ecosystem endpoints for aquatic ecosystems.

Endpoint type	Example of measures to assess endpoint
Species-level endpoints	Species productivity; status of endangered, threatened, or economic species; species diversity; key species
Community/ ecosystem-level endpoints	Water quality; flow patterns; hydrodynamics; fish productivity and diversity; invertebrate productivity and diversity; plant productivity and diversity; detrital dynamics; habitat quality; habitat structural diversity; trophic structure; biogeochemical cycling; spatial dynamics (dispersal, migration)
Landscape-level endpoints	Spatial mosaic of habitat types (channel complexity); flood frequency and intensity; drought frequency and intensity; anthropogenic disturbance; climate change; sediment/ materials transport

Source: Modified from Harwell and others (1999)

Ecological indicators should be selected on the basis of their intrinsic importance (measure a species or process directly), the ability to serve as an early warning indicator (rapid identification of potential effects), the ability to serve as a sensitive indicator (reliability in predicting response), or the ability to stand in for a process (Harwell and others, 1999; Dale and Beyeler, 2001). Additional considerations include the ease and cost of monitoring and the availability of historical data. A challenge in selecting the appropriate suite of indicators is determining which of the numerous measures adequately characterize the aquatic ecosystem, yet are simple enough to be effectively and efficiently monitored and modeled. This challenge includes identifying indicators thought to be flow sensitive so that they will reliably link changes taking place in the ecosystem to changes in hydrologic regime. The use of too many indicators may be cumbersome, but if too few indicators are adopted, they may not adequately capture the multiple levels of complexity within the aquatic ecosystem.

5.2.3
Formulate Study Design

Before completing a study design, the Agencies and stakeholders participating in sub-basin workgroups will reach consensus on the technical studies that need to be conducted to address identified objectives and indicators. The study design will include the summary of available data, results of preliminary analyses and reconnaissance surveys, assessment of current conditions, and a conceptual model of the river system. It will also include study goals, objectives, and indicators developed with stakeholders. The Agencies will add descriptions of proposed technical studies and how they address specific objectives and indicators. These descriptions will include study site locations, data collection methods and protocols, and multidisciplinary coordination. The draft study design will be submitted for peer review and comment. Necessary revisions will be incorporated before a final study design is approved by stakeholders and the Agencies.

Table 5-4. Texas Commission on Environmental Quality site-specific uses and criteria for the Lower Sabine River.

TCEQ segments		Uses			Criteria						
Segment number	Segment name	Recreation	Aquatic life	Water supply	Cl^{-1} mg/l	SO_4^{-2} mg/l	TDS mg/l	DO mg/l	pH range SU	Bacteria #/100ml	Temp. F
0502	Sabine River above tidal	Contact recreation	High	Public supply	50	50	200	5.0	6.0-8.5	126/200	91
0503	Sabine River above Caney Creek	Contact recreation	High	Public supply	50	50	200	5.0	6.0-8.5	126/200	91

Source: 30 Texas Administrative Code §307.10(1) Appendix A
mg/l=milligrams per liter
Cl^{-1}=Chloride ion
SO_4^{-2}=sulfate ion
TDS=total dissolved solids
DO=dissolved oxygen
pH=potenz hydrogen, hydrogen ion concentration
SU=standard units
/100ml=per 100 milliliters

Table 5-5. TCEQ site-specific uses and criteria for tributaries of the Lower Sabine River.

Tributaries to TCEQ Segments		Uses			Criteria	
Segment number	Tributary name	Recreation	Aquatic life	Water supply	Dissolved oxygen mg/l	Bacteria #/100ml
0503	Caney Creek	Contact recreation	High		5.0	126/200
0503	Unnamed tributary of Dempsey Creek	Contact recreation	Intermediate		4.0	126/200

Source: 30 Texas Administrative Code §307.10(4) Appendix D
mg/l=milligrams per liter
/100ml=per 100 milliliters

Table 5-6. Attributes of aquatic life use categories.

Aquatic life use	**Habitat characteristics**	**Species assemblage**	**Sensitive species**	**Diversity**	**Species richness**	**Trophic structure**
Exceptional	Outstanding natural variability	Exceptional or unusual	Abundant	Exceptionally high	Exceptionally high	Balanced
High	Highly diverse	Usual association of regionally expected species	Present	High	High	Balanced to slightly imbalanced
Intermediate	Moderately diverse	Some expected species	Very low in abundance	Moderate	Moderate	Moderate
Limited	Uniform	Most regionally expected species absent	Absent	Low	Low	Severely imbalanced

Source: Texas Administrative Code §307.7(b)(3)(A)(i)

6 *Hydrology and Hydraulics*

As noted by Richter and others (2003), a river's hydrologic flow regime is recognized as a "master variable" that drives variation in other components of the river ecosystem. As a result, evaluations of a river's hydrology and hydraulics play a key role in developing instream flow components. In addition to providing an analysis of the hydrologic regime, these evaluations assist with biological, geomorphic, and water quality studies. Hydrologic data will also assist in developing all four instream flow regime components: subsistence flows, base flows, high flow pulses, and overbank flows. In addition, hydraulic modeling will provide an estimate of the extent of various habitats during base flows and of inundation during overbank flows.

Because water diversions affect the flow regime in frequency, timing, duration, rate of change, and magnitude of streamflow, hydrologic data will help assess the changes that have occurred in hydrologic regimes. For example, hydrologic time series data can be analyzed to assess current conditions, calculate alterations in quantity and timing of flows, and characterize the physical behavior of water in the system at an ecologically relevant scale. Low flow statistics, such as the seven-day, two-year low flow known as 7Q2, will provide information that will ultimately assist in developing subsistence flow recommendations. Median and percent exceedence flow statistics will likewise assist in developing base flow recommendations. High flow and flood frequency statistics will aid in developing high flow pulse and overbank flow recommendations. Flow statistics will also be used to describe hydrologic conditions as wet, average, or dry. Hydrologic evaluation methods are discussed in Section 6.1.

Hydraulic modeling will be conducted to develop flow component recommendations. Two-dimensional hydraulic modeling will be used to determine in-channel hydraulic conditions over a range of flows. These modeling efforts will assist in studying the relationship of flows to habitat conditions, which, in turn, will help determine suitable base flows. A one-dimensional hydraulic model will be used to estimate inundation of riparian areas and assist in developing overbank flows. Additional hydraulic modeling may be conducted in response to concerns related to sub-basin studies. Hydraulic modeling techniques are discussed in Section 6.2.

6.1
HYDROLOGIC EVALUATION

A hydrologic evaluation of a river's flow regime is required in order to determine instream flow requirements that support the river ecosystem. This evaluation should consider both the condition of the river prior and subsequent to human-induced flow modifications. Most major rivers in Texas have been significantly modified over the last 30 or more years. During this extended period of modification, significant changes may have occurred, which should be considered when making instream flow recommendations.

Across Texas, natural flow regimes exhibit tremendous variability and include seasonal periods of low flow, short duration floods, and stable base flows. These large variations can be attributed to the geographical variation and size of the state, which experiences disparate regional precipitation patterns (average annual rainfall is 58 inches or 147 centimeters per year in coastal East Texas but only 8 inches or 20 centimeters in arid West Texas) and seasonal patterns of rainfall. Texas has 3,700 named streams and rivers, very few of which can be considered free-flowing. Every major river basin in Texas has been impounded, and nearly 6,000 dams have been constructed statewide (Graf, 1999). Nearly 200 reservoirs constructed for flood control and/or municipal supply have a storage capacity greater than 5,000 acre-feet (6.2 million cubic meters). For most sub-basins in Texas, the available reservoir storage volume is large enough to capture more than twice the average annual rainfall-runoff volume. This large reservoir storage-to-runoff ratio makes Texas rivers and streams vulnerable to flow regime changes and associated ecological effects.

Many aquatic species have specific habitat and life history requirements that are intimately linked to seasonal trends and natural flow regimes (Richter and others, 1996). Although aquatic ecosystems can respond to alterations in the natural flow regime, there is usually some cost to biological integrity and diversity. Fishes in prairie stream communities, for example, are adapted to harsh environmental conditions, such as low flow events, but may also have spawning activities keyed to high flow events. When flow conditions are altered, generalist species may dominate aquatic communities at the expense of specialists adapted to flowing water habitats. Shifts in community structure can be significant downstream of reservoirs, and negative impacts on upstream fish communities have also been documented (Winston and others, 1991).

The health and maintenance of various riparian areas, hardwood bottomlands, and associated wetland ecosystems is also intimately linked to natural flow regimes. Attenuation of high flows by flood control projects and water supply reservoirs influences the long-standing relationship between streams and riparian areas. This attenuation disrupts exchanges of nutrients, organic materials, sediments, and water between stream resources and floodplains causing detrimental effects on riparian ecosystems. Consequences can be far reaching because rivers, streams, and riparian areas cumulatively assimilate large volumes of nutrients and organic materials from both natural and human sources, such as wastewater and nonpoint source runoff.

In order to protect river ecosystems, the National Research Council recommended that the Texas Instream Flow Program specify four hydrologic flow components (NRC, 2005). These components are overbank flows, high flow pulses, base flows, and subsistence flows. Each plays an important part in maintaining the health of a river ecosystem. After a complete evaluation of the hydrologic regime and other technical studies, the instream flow program will identify a flow regime that includes these four components. For a specific sub-basin, additional flow components may also be required.

Maintaining riparian areas depends on the timing, duration, and magnitude of overbank flows. These flows inundate active floodplain areas and can connect the main channel to sloughs, adjacent bayous, and other types of riparian wetlands. A lack of overbank flows may result in changes in the vegetative community of riparian areas, for example, shifts from hardwood bottomland to upland vegetation.

High flow pulses are important for channel maintenance. Accumulation of sediments or vegetative encroachment may occur if high flow pulses with appropriate magnitude, frequency, and duration are not provided. These and other processes can result in reduced channel capacity to handle flood flows.

In addition, overbank flows and high flow pulses create and maintain physical habitat features within the channel. These two components recruit large woody debris to the channel, maintain the depth of pools, and sculpt other features of the channel that maintain habitat suitability and diversity.

Diminished base flows, largely because of direct diversions, inadequate reservoir releases, and pumping that reduces groundwater flow to streams, cause reductions in habitat diversity and availability, loss of stream productivity, and alterations to trophic and community structure. Reduced base flows can also cause biologically important changes in water quality characteristics, such as reduced assimilative capacity, reaeration, and thermal buffering capacity, as well as alterations to nutrient dynamics and organic matter processing.

Subsistence flows are naturally occurring low flow events. Humans, however, may have increased the duration and frequency of these events. This can seriously affect fish and wildlife resources. Desiccated streams obviously provide little aquatic habitat, and extended periods of low flow generally result in pool habitats separated by dry reaches of streambed. If pools become severely reduced, temperatures can rise to lethal levels and dissolved oxygen levels may be insufficient for the survival of many species. Consequently, populations of aquatic organisms needed for recruitment may not exist once streamflows return to base flow levels. The threat of significant, adverse effects on river and stream communities is especially serious in over-appropriated river basins such as the Rio Grande. In addition, the integrity of spring-fed ecosystems is compromised by excessive groundwater pumping rates. Of the 281 springs in Texas identified by Brune (1981) as historically significant, more than one quarter (80) no longer flow, and those that remain experience periods of significantly diminished discharges.

Alternatively, some river systems may experience negative ecological impacts due to increased subsistence flows. This can occur when water is stored in reservoirs during the normally wet portion of the year and returned to the river as return flows or irrigation releases during the normally dry portion of the year. Interbasin transfers may also result in increased subsistence flows in some basins. Increased subsistence flows may allow exotic species to survive and dominate in areas previously hospitable only to highly adapted native species.

A detailed hydrologic evaluation is required to accurately analyze the effects of a modified flow regime on a river system. The evaluation must address runoff inputs, water diversions, water impoundments, flood control structures, and proposed water development projects on the river system. The analysis must evaluate both intra- and interannual flow variations (Richter and others, 1996). Hydrologic evaluation in support of the instream flow studies will include analysis of both historical and naturalized flow data. Historical flow data, described in Section 6.1.1, are available from streamflow gaging sites within the state. Naturalized flow data are developed by removing the estimated effects of human diversions from the historical data. This process is described in Section 6.1.2.

6.1.1

Historical Flow Data

Historical streamflow information will be compiled from U.S. Geological Survey and other gaging stations located within the project area. Statistical analysis will be performed on the reported daily averaged flows to determine median, average, and percentile flows for each month, season, and year. These data can be used to determine periods of wet, average, and dry hydrologic conditions.

The entire period of record at each gage will be analyzed unless a water development project directly affects the gage data. In that case, pre- and post-development flows will be separated for individual analysis.

In some cases, a gage site may not be present in the immediate vicinity of a study site; however, the existing network of U.S. Geological Survey gaging sites is designed so that each significant watershed contains its own unique gaging station. The network also ensures that there are sufficient "representative" watersheds gaged throughout the state so that flow on an ungaged watershed can be estimated with reasonable accuracy. Within the same river, watershed area multipliers may be used to compare projected flow at a study site to the flow measured at the nearest upstream or downstream gage. If area multipliers are inappropriate for a particular site, hydrologic models like HEC-HMS (HEC, 2005) or TxRR (Matsumoto, 1995) that account for land use and soil type may be used to predict runoff from rainfall data.

To use a hydrologic model for a rainfall-runoff evaluation, the watershed of the study site must be delineated. Watershed delineation will be performed using the best quality topographic information available. Hydrologic Unit Code watershed boundaries will be used in conjunction with Digital Elevation Models or National Elevation Datasets at 10- or 30-meter resolution, published by the U.S. Geological Survey to delineate watershed boundaries. A data layer of 12-digit Hydrologic Unit Code watershed boundaries is currently being developed for most of Texas by the Natural Resources Conservation Service and U.S. Geological Survey. If these models or data sets are unavailable, digital raster graphic or U.S. Geological Survey 7.5 minute topographic quadrangle maps will be used to assist in delineating watersheds. Spatial representation of rivers and lakes (based on U.S. Geological Survey topographic quad sheets corrected using aerial photography) can be obtained from the Texas Natural Resources Information System. Much of this work can be handled easily in a GIS environment. Information from the Texas Natural Resources Information System can be obtained at this Web site: www.tnris.state.tx.us

6.1.2

Naturalized Flow Data and Water Availability Modeling

Since natural river flow regimes can no longer be observed on most rivers in Texas, they must be estimated from available data. This can be accomplished by accounting for reservoir attenuation and evaporation and removing known return flows from and adding diversions to a historical flow record. However, in cases where an on-channel reservoir or flood control structure exists upstream of a study site, pre-impoundment flows downstream of the site or flows upstream of the reservoir usually provide a better means of determining naturalized flows than estimating and accounting for reservoir attenuation and losses.

Water availability models used for water rights permitting in Texas include naturalized flow sequences on a monthly time step as part of their input data sets. Input data for specific river basins can be obtained from the Texas Commission on Environmental Quality Web site: www.tceq.state.tx.us/permitting/water_supply/water_rights/wam.html

Because flow variations on shorter time steps are important to riverine ecosystems, monthly summary volumes are inadequate to evaluate instream flows. Naturalized flow data with a daily time step will be required for most studies in the instream flow program. In addition, areas immediately downstream of hydropower operations may occasionally require hourly flow data to evaluate current conditions. However, even in these cases, characterization of natural conditions (without hydropower operation) would rarely require data with shorter than a daily time step.

Daily average naturalized flows may be calculated by disaggregating monthly naturalized flows to a daily time step and routing daily flows through the river network. Options to complete this process have been included in the most recent version of the Water Rights Analysis Package, which forms the basis for water availability modeling in Texas (Wurbs, and others 2005). The most appropriate method for flow disaggregation and calibration of routing parameters will be determined for each sub-basin study. Once daily naturalized flows are calculated, they will provide a baseline for estimating the effect of allocated water rights by applying each project's operating rules to the same daily time series.

Because many factors can modify the natural flow regime, caution will be exercised when interpreting results. For example, water right diversions, in-channel impoundments, and changes in the watershed that affect timing and quantity of runoff (such as an increase in impervious cover associated with urban development) can all affect results. In addition, the daily distribution of naturalized flows is generated from flow gage data measured in a system that may have already been impacted by diversions.

6.1.3

Flow Frequency Analysis

Frequency analysis on the time series of flows can provide a good idea of both the "flashiness" of the river (its tendency to carry a large percentage of its flow in large, infrequent events) and the degree of human impact. Flow data for naturalized, pre-development, current and/or other conditions may be analyzed and compared. Flow duration curves are particularly useful for assessing daily flow data. These curves are developed by first ordering the time series data from largest to smallest. The percent of time that flow exceeds a certain value (percent exceedence) is then calculated by dividing the number of days with flow equal to or greater than the value by the total number of days in the time series. A flow duration curve is obtained by plotting flow versus percent exceedence. Changes in the hydrologic regime can be visualized by plotting flow duration curves for pre- and post-development conditions on the same graph (Figure 6-1).

Cumulative probability curves are also useful in assessing daily flow data. Developing these curves requires ordering the time series data from smallest to largest. The percent of time that flow is below a certain value (cumulative probability) is calculated by dividing the number of days with flow equal to or less than the value by the total number of days in the time series. A cumulative probability curve is obtained by plotting flow versus cumulative probability (Figure 6-2.) By inspecting cumulative probability curves, suitable flow rates at which to develop hydraulic models for habitat modeling can be determined. Flow quantity is considered to be a limiting factor for habitat at low flow rates. At the median (50th percentile) flow rate and above, flow quantity is not believed to be a limiting factor for habitat. Therefore, a flow range from the median flow down to the 10th percentile is considered appropriate for habitat modeling. As a general rule, at least six flow rates across this range are chosen for modeling. In order to allow additional validation of the hydraulic model, flow rates when biological sampling or other fieldwork took place may also be modeled.

6.2

HYDRAULIC EVALUATION

Hydraulic evaluation based on numerical modeling provides input for developing both overbank and base flow components. For overbank flow development, one-dimensional hydraulic modeling will provide water surface elevations to estimate the extent of inundation in riparian areas associated with various flow rates. Nislow and others (2003) used such an approach to make a "spatially explicit assessment of hydrologic alteration." For base flow development, a two-dimensional hydraulic model will be used to provide input for a habitat model. Additional hydraulic modeling may be conducted in response to concerns related to a specific river sub-basin.

Three components of an instream flow study, as they pertain specifically to hydraulic evaluation, are discussed in the following sections: the choice of a representative river reach, field data collection, and the application of a hydraulic model.

6.2.1
Choosing a Representative Reach

In most cases, it is impractical to monitor, analyze, and hydraulically model an

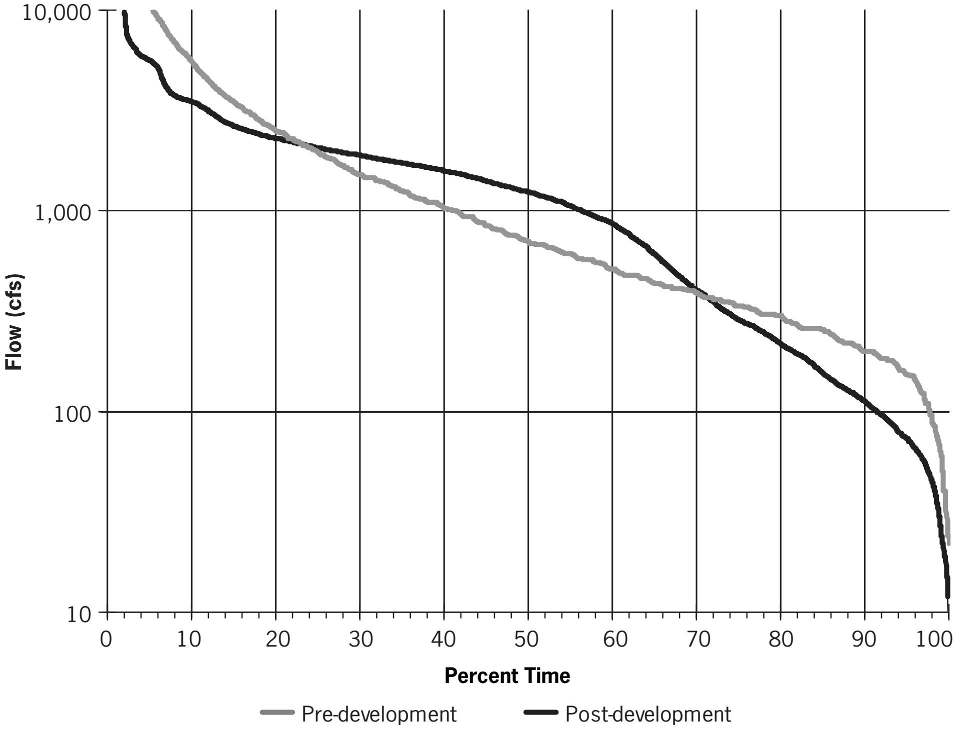


Figure 6-1. Flow duration curve calculated from daily data for pre-development and post-development conditions.

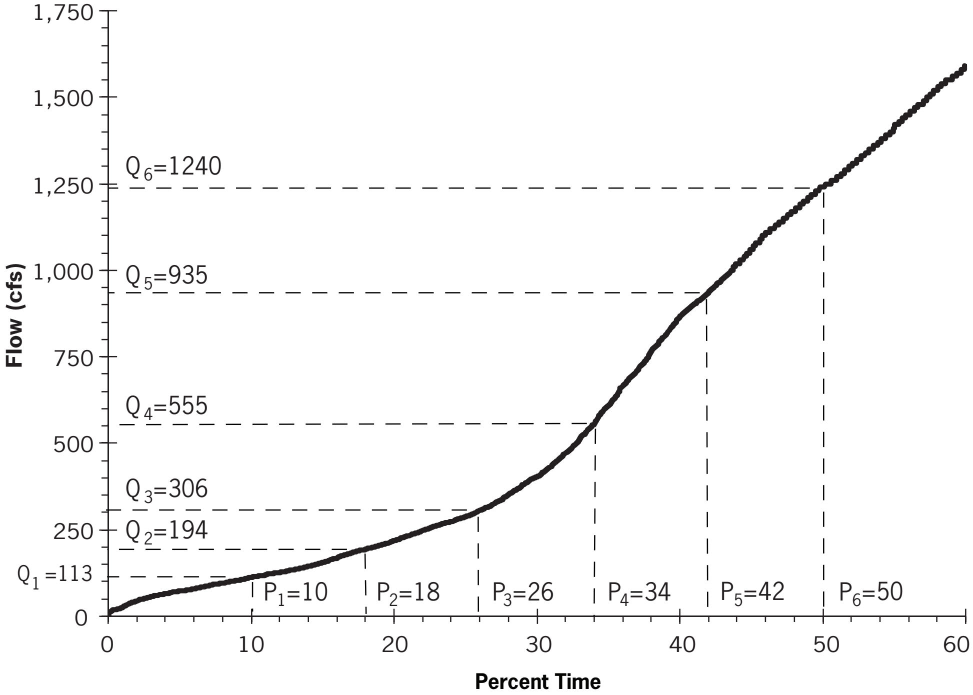


Figure 6-2. Cumulative probability curve with flow rates suitable for habitat modeling.
cfs=cubic feet per second, 35.3 cubic feet per second is equal to 1 cubic meter per second

entire river. Instead, one or more representative reaches are selected in order to estimate conditions for the river as a whole. Representative study reaches are selected using a combination of criteria. Within a river sub-basin, one or more reach-length study sites may be selected, each reflecting the unique characteristics of a particular region of the sub-basin. A study reach may be selected to address a particular concern in a specific sub-basin; for example, a reach may be located directly downstream of a proposed diversion.

The possible length of a study reach is limited by the hydraulic model that will be used. The lower computing power required by a one-dimensional model makes it feasible to model a relatively large study area, for example, an area extending across the active floodplain and along the river for many miles. The greater computational power required by two-dimensional models limits their feasibility to smaller study areas, such as an area extending across the channel and along the river for no more than a few miles. In practice, this is not a severe limitation because the purpose of the study also limits the required length of the study reach. For example, habitat studies, which employ two-dimensional hydraulic models, do not require study reaches of more than a mile or two in length (1.6 to 3.2 kilometers).

The choice of study site length and boundary locations is influenced by many factors, including the requirements for accurate hydraulic modeling. For one-dimensional hydraulic modeling, a common rule-of-thumb has been to choose a site whose length is 20 to 30 channel widths or of sufficient length to encompass one complete meander wavelength (Leopold and Wolman, 1957; Waddle, 2001). These same minimum criteria are applicable to multidimensional modeling; however, rather than establish reach length based upon rules-of-thumb, reach length is established to ensure that a representative distribution of channel structures and bed forms common to the study sub-basin are present. A representative reach whose frequency of pools, riffles, and runs corresponds to the frequency of occurrence of those forms in the sub-basin gives a good representation of the response of the entire sub-basin to some disturbance.

Upstream and downstream boundaries of the hydraulic model are chosen with the behavior of the numerical model in mind. Complicated banks and bathymetry near the upstream and downstream boundaries can cause numerical instability problems for hydraulic models. Selecting upstream and downstream boundaries that minimize such conditions is, therefore, standard practice. More complicated banks and bathymetry are limited to the interior of the modeled section. In order to obtain suitable boundaries, the modeled reach may be extended outside of the area of interest. In this case, extraneous hydraulic model information will be removed from the study reach analysis.

6.2.2

Field Data Collection

To use a physically based hydraulic model, at least three boundary conditions must be specified: upstream boundary flow rate, downstream boundary water surface elevation, and bathymetry. Flow rate at the upstream boundary and water surface elevation at the downstream boundary describe the flow of water mass into and out of the system, respectively. Spatial variations in flow within the study reach are most influenced by representative structures and bed forms located within the study reach, so the accuracy of model output of depth and velocity depends on the accuracy of the data that describe the bottom bathymetric boundary (Carter and Shankar, 1997; Lane and others, 1999). Furthermore, the scale at which information about the spatial variability in flow is desired dictates the scale at which both bathymetric data and model verification data (velocity and depth at specific locations at specific flows) are collected.

Flow rates at the study site will be determined by field measurements. A sufficient number of measurements will be collected to develop a rating curve describing the river stage versus discharge relationship. Many instrument options exist for measuring river flow rate, including acoustic doppler current profilers, portable acoustic doppler velocity meters, electromagnetic velocity measurement devices, and mechanical velocity measurement devices. For channels with maximum depth greater than 1.5 meters (about 5 feet), a boat-mounted acoustic doppler current profiler is used to measure flow. It calculates flow by integrating sonically measured vertical velocity profiles across a lateral transect perpendicular to flow direction (Gordon, 1989). Alternatively, a velocity meter is used to measure point velocities that are, in turn, used to integrate cross-sectional flow by traditional U.S. Geological Survey flow measurement methods (Prasuhn, 1987). In shallow conditions (depths less than 0.66 meters or 2.2 feet) where it is possible to wade across the river, hand-held devices are more practical than an acoustic doppler current profiler for flow measurement. In order to verify two-dimensional hydraulic model output, velocity measurements will also be taken at a number of points within a study reach.

Flow rates measured at the site may be compared with flow rates reported at nearby U.S. Geological Survey gaging stations. Flow statistics calculated using historical gaging station data will be used, along with an appropriate multiplier, to estimate flow regime statistics at the study reach site. For sites with little hydrologic correlation to a gaging station, additional analysis will be performed as described in Section 6.1.1.

Water surface elevation data will be collected at upstream and downstream boundaries, as well as at any intermediate areas that exhibit significant changes in water surface slope. Elevation can be determined using either traditional differential leveling or vertically accurate GPS techniques. Semipermanent vertical benchmarks and pressure transducers installed at upstream and downstream boundaries of a reach will remain in place for the duration of the study. Upstream and downstream water surface elevation measurements will be used as boundary conditions for modeling. Additional water surface elevation measurements will be used for verifying both one- and two-dimensional model output.

Bathymetric data for one-dimensional hydraulic models will be collected on channel cross sections that extend beyond riparian areas of interest. Data in out-of-channel areas will be collected with traditional or GPS surveying equipment. For streams too large to wade, data will be collected in the channel by way of a boat-mounted differential GPS linked to a depth sounder, and the number of channel cross sections required will be a function of channel complexity. In general, the greater the number of changes in discharge, slope, shape, and roughness along the channel, the greater the number of cross sections required to characterize hydraulic behavior. Data related to relative hydraulic roughness of channel and overbank areas will be collected at the same time. For a complete description of data collection requirements for one-dimensional hydraulic modeling, see Brunner (2002).

Bathymetric data for two-dimensional models will be collected at very high spatial resolution using a boat-mounted differential GPS linked to a depth sounder. Depending on conditions (including tree canopy, overhead banks, availability of correctional signals), it may be impossible to obtain positional data with sufficient vertical accuracy with available GPS equipment. In such cases, a network of pressure transducers will be used to record water surface elevations at locations along the study reach where significant changes in water surface slope occur (such as the head and foot of riffles and pools). The water surface elevation at any location in the study reach can then be interpolated. The vertical component of bathymetric data may be obtained by subtracting the fixed distance from the water's surface to the boat-mounted depth sounder's transducer face.

Because quantifying the spatial variability of habitat use is the objective of habitat flow studies, sufficient bathymetric data must be collected to describe the causes of spatial variation in flow. Dominant bed forms, banks, outcrops, and other channel structures that influence flow patterns within the reach must be resolved at a scale sufficient to model the flow patterns caused by those structures. If necessary, additional bed and bank elevation data may be collected using traditional surveying or other techniques to describe the cross section above the median flow water line.

Combining flow rate data with water surface elevation data, a stage-discharge curve for the study reach will be developed (Figure 6-3). Such a curve is used to develop input data (water surface elevations) for hydraulic modeling across a range of flows of interest. The curve is developed by measuring several water surface elevations (stages) and discharges and fitting a curve to the data. The shape of the stage-discharge curve is determined by the hydraulic control downstream of the measurement point. For natural stream channels, hydraulic control may be dominated by a single feature, such as a bedrock outcrop, gravel riffle, or sand bar or may be the result of a number of features along the downstream channel. Because hydraulic

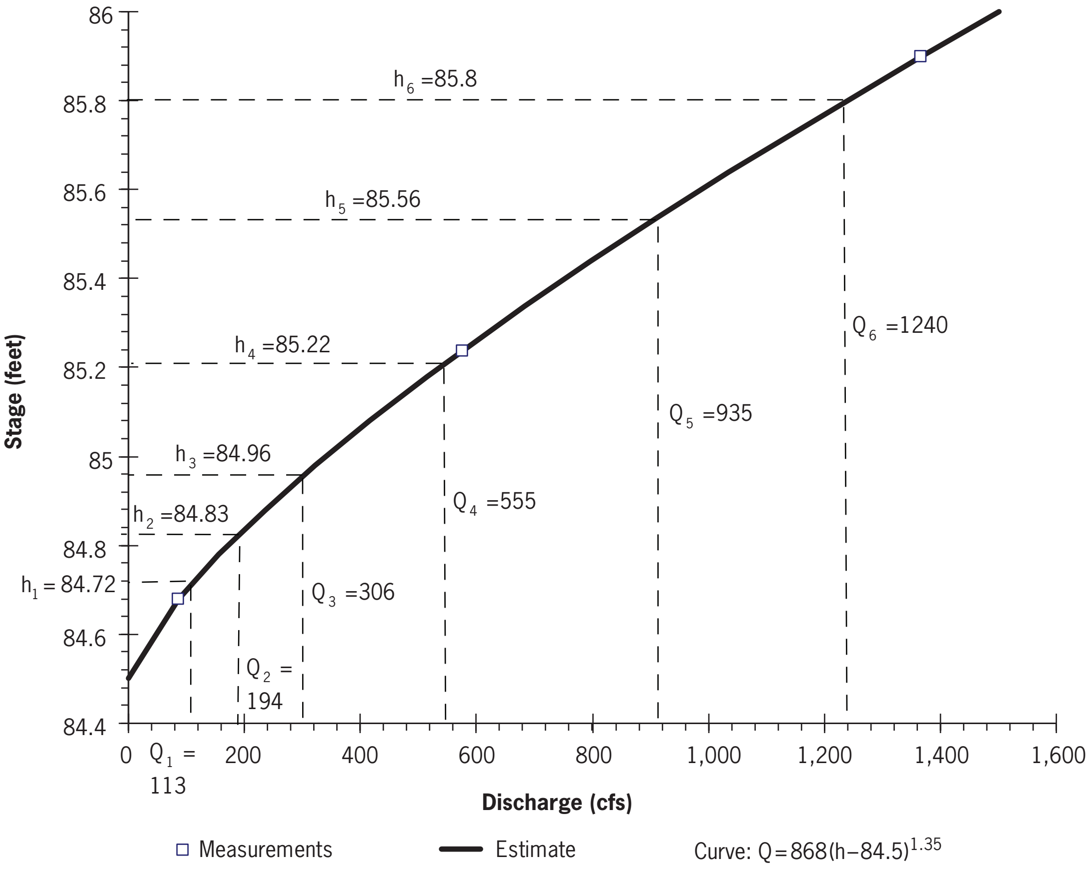


Figure 6-3. Stage-discharge curve developed for hydraulic model input.
cfs=cubic feet per second, 35.3 cubic feet per second is equal to 1 cubic meter per second

control may vary with discharge (larger flows submerge different features in the channel or floodplain), stage-discharge curves should not be used to estimate water surface elevations well beyond the range of measured data. When conducting two-dimensional hydraulic modeling in support of habitat studies, flows of interest range from about the 10 to 50 percent cumulative probability flows. Hydraulic control can also change over time as downstream features, such as sand bars, change. Therefore, stage-discharge curves developed for hydraulic modeling input are not suitable (in most cases) for estimating water surface elevations over extended time periods.

6.2.3

Hydraulic Modeling

A numerical hydraulic model will be used to model the distributions of water surface elevation, depth, and velocity within the study site for a particular flow of interest. The results will be used to evaluate overbank flows based on the expected inundation of riparian areas or to evaluate base flow conditions based on habitat availability. There are many options for modeling the water surface elevation, depth, and velocity nonuniformities within a study site, the most basic option being choice of model dimensionality. One-dimensional hydraulic models calculate the average water surface elevation, depth, and velocity for a cross section or portion of a cross section. Multidimensional hydraulic models (both two- and three-dimensional) are capable of resolving depth and velocity at many points in a cross section. One-dimensional models are generally capable of providing water surface elevation data suitable for evaluating inundation of riparian areas during overbank flows. Two-dimensional hydraulic models have been used most recently for habitat flow studies in Texas. Hydraulic models suitable for study objectives will be chosen for specific sub-basin instream flow studies.

One-dimensional hydraulic modeling

One-dimensional hydraulic models require relatively little computational power and their numerical basis is less difficult to understand than multidimensional models. They require cross-sectional bathymetry data, and the modeled channel length must far exceed the channel width. These models are suitable for studies investigating parameters, such as water surface elevation or chemical concentrations that vary along the length of the channel and are relatively constant across the channel width. They are often used to study water quality and overbanking flood flows. Regulatory water quality models in Texas traditionally rely upon one-dimensional hydraulic advection models to determine constituent transport. Modeling of flood-flow water surface profiles and overbanking can also be performed with a one-dimensional model, such as HEC-RAS, WSP2, or MIKE11. Until the mid-1990s, habitat studies related to base flows also relied on one-dimensional hydraulic models. However, since most rivers have spatially complex hydraulic habitats, including across-channel velocity variations, many investigators have found two-dimensional models more suitable for habitat flow studies (Leclerc and others, 1995; Moyle and others, 1998; Railsback, 1999; Crowder and Diplas, 2000). One-dimensional models remain useful for many studies related to water quality and water surface elevation.

There are a number of one-dimensional hydraulic models that may be appropriate for modeling inundation of riparian areas (for example, HEC-RAS, WSP2, and MIKE11). Although other models may be acceptable, the Agencies prefer HEC-RAS for overbank flow studies for several reasons. The HEC-RAS code is well known, and extensive training and documentation is available for this software (Annear and others, 2004). Additionally, it has been used with success for similar studies in other states (Nislow and others, 2003; Philip Williams and Associates, 2003) and within Texas (Freese and Nichols, 2005). The HEC-RAS model uses energy and momentum equations to calculate water surface elevations for both steady and unsteady flow and is specifically designed for floodplain management applications. (Additional information on HEC-RAS can be found in Brunner (2002) and Annear and others (2004)).

Multidimensional hydraulic modeling

Multidimensional hydraulic models offer a number of features that make them especially useful in habitat studies. They quantify lateral (across the channel) circulation patterns, velocity variation, and water surface elevation variation that cannot be quantified with one-dimensional models. Additionally, complicated river structures such as islands, cutoffs, backwaters, and debris can be incorporated into multidimensional models (Bates and others, 1997). Multidimensional models produce a spatially explicit representation of hydraulic habitat offering expanded options for instream habitat analysis (Bovee, 1996; Hardy, 1998).

Both two- and three-dimensional hydraulic models are available for use in studies of habitat during base flow conditions. Two-dimensional models traditionally used in river studies are depth-averaged so only horizontal variations in flow are simulated. Electrofishing and other biological data collection techniques allow development of hydraulic habitat descriptions in terms of mean column velocity, a good match for two-dimensional models. Three-dimensional models capture both horizontal and vertical velocity variations, which are modeled in vertical layers above each node. Velocities at specific points in the water column would be resolvable with three-dimensional models, but hydraulic habitat requirements are seldom described in this manner. Three-dimensional models may be applied if strong vertical velocity gradients exist within a study reach or if knowledge of three-dimensional flow variation would improve the analysis of habitat availability. However, in most cases, a two-dimensional model will suffice.

There are myriad formulations and assumptions incorporated into a typical multidimensional hydraulic model. Model formulations applicable to hydraulic evaluations in Texas instream flow studies are discussed below.

Governing equations

Multidimensional fluid mechanics models applicable to river studies are built upon the Navier-Stokes equations for fluid flow. Since computational limitations preclude direct solution of the exact equations, most available hydraulic models are based upon the shallow water form of the Reynolds-averaged Navier-Stokes (RANS) equations that include the Boussinesq approximation and assume hydrostatic pressure. A detailed explanation of the general modeling formulations is not presented here because it is presented in many manuscripts, texts, and referenced literature (see King and others, 1975; King, 1982; USACE, 1993; Leclerc and others, 1995; Walters, 1995; Finnie and others, 1999). Additionally, each specific model employs slightly different formulations, and an exhaustive discussion of all available models is beyond the scope of this text.

The assumptions, simplifications, and solution methods all place limitations on the types of hydraulic problems that can be solved by a particular model. For example, a depth-averaged, shallow water RANS model is not strictly applicable to situations in which large vertical velocities are present. With such limitations in mind, a model can be chosen to describe adequately the hydraulic conditions at each study site.

For modeling a typical river reach in

Texas, the shallow water RANS equations are generally applicable because hydraulic conditions are primarily subcritical, low gradient, and without significant density effects (no surface freezing and no saline tidal water). When considering overall channel hydraulics, the horizontal velocity gradients are more important than vertical velocity gradients, allowing a depth-averaged (two-dimensional) model implementing the RANS equations to be used (Leclerc and others, 1995; Vadas and Orth, 1998; Lane and others, 1999; Crowder and Diplas, 2000). However, two-dimensional depth-averaged models are less applicable where three-dimensional flow effects dominate, such as in the immediate vicinity (within centimeters or inches) of large woody debris. Unfortunately, the extremely small grid scale required to address these types of problems limits the usefulness of applying three-dimensional models.

An additional limitation to applying most two- and some three-dimensional hydraulic models is presented by the presence of steep bed gradients (slopes greater than 20 percent) oriented in the direction of flow. Such conditions cause vertical pressure gradients that lead to possible flow separations. Modeling the effect of vertical pressure gradients is not strictly possible with a depth-averaged, hydrostatic model using the shallow water equations with the hydrostatic assumption (this applies to most two- and some three-dimensional models). Smoothing the bathymetry to remove steep slopes may reduce slope-induced model convergence problems. However, this introduces another level of separation of the model from the observed system. Quantifying the error introduced by slope smoothing is difficult. Fortunately, these conditions do not occur frequently in Texas rivers.

Solution methods

Models relying on the finite element or the finite difference solution method make up the majority of available hydraulic models, although finite volume methods are gaining popularity. Finite element models have been used extensively for instream flow studies because of their ability to incorporate irregular elements that describe irregular boundary geometries and to adequately resolve flow patterns diagonally across each element (Leclerc and others, 1995; Mathews and Tallent, 1996; Austin and Wentzel, 2001; Osting and others, 2004a; 2004b). This aspect allows use of finite element models with nodes oriented in geographically correct locations, that is, with irregular elements that follow the patterns of a sinuous river.

Finite difference models give best results with regular elements and when flow patterns trend generally in the same plane as the element edges. In instances where flow can potentially be trending at any angle with respect to the regular elements (in the instance of a sinuous river), a finite difference model may not perform as well as a finite element model and may require a correction to the coordinate system. Curvilinear coordinate system transformations have been used with success (Hodges and Imberger, 2001), but the transposition of geographically correct node locations to a curvilinear reference frame introduces a level of complexity that is easily bypassed by using a finite element model. A finite difference model should, however, be considered for use if some crucial aspect is available in the finite difference model (for example, non-hydrostatic solution). Finite difference models are also faster for a given cell resolution than finite element models. For models with very fine cells and very large domains, the computational speed of finite difference models may prove beneficial.

Numerical mesh

A high-resolution mesh will be generated on which the numerical hydraulic model will calculate depth and velocity. Within guidelines that are discussed below, appropriate mesh resolution will be ultimately determined by engineering judgment and experience. Areas with complex hydraulics (steep longitudinal bathymetry, bridge areas, island areas, flow restrictions, and flow obstructions) will be afforded more elements than simple areas with relatively uniform bathymetry.

The mesh boundary will be established using a bathymetry data point file that consists of water's edge horizontal position data. These data points can be collected at high flows using a laser range finder coupled with a differential GPS. Alternatively, recent Digital Orthographic Quarter Quadrangle aerial photos may be used in conjunction with the extent of the bathymetry point file to establish the mesh boundary.

The horizontal distribution of mesh elements should be carefully controlled since their shape and orientation affect the accuracy of model results (Freeman, 1992). For one model, RMA2, a discussion of element shape requirements is included in the users' manual, with the guidance that elements should not have interior angles less than 10 degrees, should be planar (no concave or convex elements), and the area of adjacent elements should not differ by more than 50 percent (Donnell and others, 2001). Mesh generation and visualization software, such as the Surface Water Modeling System (EMSI, 2005), make it easy to evaluate meshes and implement such requirements.

The mesh should not be generated at a spatial scale significantly finer than the available bathymetry data. Bathymetry significantly affects model output (Carter and Shankar, 1997; Lane and others, 1999; Crowder and Diplas, 2000). If accurate bathymetric data are not available, the mesh should remain coarse to avoid resolving velocity fields over a bed form that may not truly be present. Similarly, minimum mesh size will be limited by the assumptions of the specific model that is being used. The horizontal resolution of cells used in fish habitat utilization analysis is generally between 2 and 5 square meters (about 20 to 55 square feet). Therefore, a hydraulic mesh of comparable resolution will provide adequate resolution of macroscopic velocity fields to meet study objectives.

Bathymetry

The results of any hydraulic model depend on an accurate depiction of the bathymetric boundary condition (Carter and Shankar, 1997; Lane and others, 1999; Crowder and Diplas, 2000). The bathymetric boundary is defined by the elevation of each mesh node. At the relatively fine scale at which a mesh will be generated, accurately describing bed form will be important for modeling velocity variations. To determine the elevation of the nodes, it will be necessary to interpolate from the bed elevation data since the resolution of bathymetry scatter point data may be coarser than the hydraulic mesh. Interpolation, however, is a source of error because the traditional interpolation techniques, such as inverse distance weighting, Thiessen polygon, cubic spline, and two-dimensional kriging, do not take into account the known shape of a river channel (such as the high gradient near the banks and the relatively low gradient along the length of the channel). Some of these methods include provisions to weight the interpolation anisotropically. However, the sinuous nature of most rivers prevents use of these techniques because the proportion of anisotropy changes with changing flow direction.

To address this problem, the Texas Water Development Board developed the Mesh Elevating and Bathymetry Adjusting Algorithm and uses it for assigning elevations to nodes in the mesh. For applying the anisotropic interpolation, the changing direction of river flow is taken into account by transforming the Cartesian coordinate system into a coordinate system that follows river planform by defining distance along the flow path and from the centerline. Rectangular search areas are defined for each node that weights the node (interpolates) average elevation more heavily with bathymetric scatter data located along the flow path than with data perpendicular to the flow path. A modified inverse distance weighting algorithm is used to calculate the weighted average of the subset of scatter points (Franke, 1982).

Substrate, roughness, and moving beds

Multidimensional models apply the shear stress caused by bed roughness as a body force acting upon the column of water located above the point of calculation. The bed roughness parameters typically applied were not originally derived for this manner of application but rather for application in one-dimensional calculations of flow for an entire cross section (Prasuhn, 1987; Arcement and Schneider, 1989). The body force calculation is, however, still applicable in multidimensional models because 1) it models the friction force at the bottom boundary and the turbulence in the water column (just like it does in the one-dimensional equations); 2) the specified roughness applies over the entire domain of influence (the entire volume for which the calculation is being made); and 3) no hard and fast rules exist for roughness coefficients in either one or multiple dimensions. A numerical estimate of roughness for a one-dimensional model may be slightly different from the estimate of roughness for a two-dimensional model for the same system (say, 10 percent difference), but the actual value is no more than an estimate or an educated guess.

At higher flows, resistance caused by large-scale bed forms is stronger than the resistance caused by material roughness (grain size). Conversely, material roughness is dominant at lower flows. When modeling a range from very low flows with shallow depths to median flows with moderate depths, the roughness parameter will change.

Obstructions (such as boulders, bridge abutments, and discarded debris) that cause local velocity variations may be difficult to include in the model. Their physical size is usually much smaller than the numerical model's grid resolution, and subgrid scale effects cannot be resolved by the model. In general, the approach taken for submerged objects is to artificially increase the roughness in the area to compensate for overall hydraulic effect. For large objects that are not submerged over the range of flows and provide complete impedance to flow (such as bridge abutments), the simplest method is to modify the mesh, removing the elements in question.

In areas with sandy substrate, bed forms may change as the energy of flow changes. In the region closest to the bed, river velocity fields have a symbiotic relationship with a mobile bed. Effects of that relationship may propagate up the water column, affecting the overall hydraulics differently at varying flows. Typically, these effects are incorporated into a model by using different roughness parameters for different flows. However, if river hydraulics cannot be adequately described by altering roughness, then a three-dimensional model that couples hydraulics with sediment transport will be required.

Objects, such as large woody debris and bed forms that are clearly mobile at higher flows, pose a problem for modeling. Past experience suggests that the best approach is to model the river as a snapshot in time, that time being the day or days when bathymetry and channel geometry were measured. The object may not be observed within the study site during the next trip to the field and another may have appeared. Unless the objects clearly impede flow on a large scale and affect either or both the upstream and downstream water surface elevations, their presence is not really important for the study. On average, similar objects or bed forms are present at some location in the river at any given time.

Substrate mapping will be carried out during the collection of bathymetric data. Information on substrate can be used to initially estimate the Manning's roughness coefficient used in calibration of the hydraulic model.

Validation of model output

Validation of model output will be performed using field-collected data. Water surface elevation data collected at many points throughout the study reach for each flow of interest will be used to validate model water surface elevation output. Point velocity readings, measured during biological sampling, will be used to validate model velocity output. Additional point velocity measurements will be taken for a range of modeled flows in areas where significant hydraulic gradients are present. Horizontal and vertical velocity profiles across an entire cross section will be measured using the acoustic doppler current profiler at the downstream boundary and in areas where point velocity measurements are not available, not practical, or insufficient to define the flow.

Validation should be performed for each calibrated model and include a comparison of depth and velocity data measured in the field to depth and velocity output from the model. Such validation should be performed in many locations throughout the model's spatial domain. At a minimum, the depth and velocity measurements that are used for the flow rate calculation should be used again to compare model output across that same cross section. Additionally, depth and velocity measured at each biological sampling location should be compared to model output.

Ideally, additional depth and velocity measurements should be collected to increase confidence in each calibrated model's output. For a depth-averaged, two-dimensional model, at least three depth and velocity measurements (left margin, mid-channel, and right margin) should be taken at cross sections located one channel width apart. Alternatively, acoustic doppler current profiler cross sections can be measured at the same spacing. For three-dimensional models, vertical velocity profiles should also be measured at the same spacing.

Discussion of RMA-2

There are a number of multidimensional hydraulic models that may be appropriate for modeling habitat (RMA-2, FESWMS, CCHE2D, RMA-10, CH3D-WES, and EFDC). Some hydraulic models have been designed specifically for fish habitat studies (such as River2D, HYDROSIM, and SSIIM2D). The Texas Water Development Board has selected RMA-2 for several recent habitat flow studies for several reasons (Mathews and Tallent, 1996; Osting and others, 2004a; 2004b). The RMA-2 code is well known and has been used with success by others (Deering, 1990; King, 1992; Finnie and others, 1999; Crowder and Diplas, 2000). The model can handle wetting and drying of elements which is a necessary feature for low flow studies. The code can be modified to accept a large array of nodes and elements (typical instream flow models have used roughly 50,000 nodes and 20,000 elements). Most important, RMA-2 resolves flow features to a scale that is relevant to habitat studies. If other models are better suited to specific conditions at a specific site, they may be used. A brief discussion of the RMA-2 model is included below, but many of the concepts and modeling approaches described are applicable to other two-dimensional models as well.

RMA-2 is a two-dimensional, depth-averaged, finite-element hydraulic model that can solve steady-state and transient problems. Water surface elevation and depth-averaged velocity flow fields are calculated from the Reynolds-averaged form of the shallow water Navier-Stokes equations for turbulent flows. Bottom friction is applied using Manning's or Chezy's equation. Eddy viscosity coefficients are used to model turbulence characteristics. The code was originally developed in 1973 for the U.S. Army Corps of Engineers, with subsequent enhancements made by Resource Management Associates and the Corps' Waterways Experiment Station (Freeman, 1992; Donnell and others, 2001).

Input requirements of the model include the finite element mesh (bathymetry), downstream boundary condition (the water surface elevation), upstream boundary condition (the flow rate or initial velocity profile), bottom roughness coefficients, and eddy viscosities. With all other model settings held constant, bottom roughness and eddy viscosity are used as calibration parameters. At the discretion of the modeler, both of these parameters can be varied spatially across the domain of the model.

Bottom roughness is incorporated into RMA-2 using either Chezy's or Manning's roughness coefficients. Roughness values are user-specified based upon bed materials (substrate grain size or vegetation) and bed form. Reference materials are consulted for appropriate Manning's roughness values based upon the materials and flow conditions at the site (see Chow, 1964; Prasuhn, 1987; Arcement and Schneider, 1989; USACE, 1993).

Eddy viscosity can be described as an amalgamation of terms that include absolute fluid viscosity, Reynolds stresses, and some simplifying assumptions constructed to allow for solving the model. In RMA-2, eddy viscosity is specified for each element, and appropriate values vary with velocity, depth, and cell-length scales (Richards, 1990; Freeman, 1992). The cell Peclet number (defined in Donnell and others [2001] as fluid density times average elemental velocity, times cell length in flow direction, divided by eddy viscosity) incorporates those scales and is used to determine appropriate eddy viscosity values.

The RMA-2 manual suggests that eddy viscosity should be between 500 and 5000 Pascal-seconds and also that the cell Peclet number should be between 15 and 40 (Donnell and others, 2001). Richards (1990) presents a model in which the best replication of flow separation is achieved when the Peclet number is four. Since the appropriate eddy viscosity value depends on cell depth, velocity, and length scales, the Peclet number criterion is used to determine the absolute eddy viscosity values. For habitat flow studies, the cell Peclet number is specified between 15 and 20, resulting in eddy viscosity settings as low as 50 Pascal-seconds when using small cells (< 5 meters or 16.5 feet in length) as is typical for habitat flow studies. An absolute eddy viscosity value for each element can be individually assigned, but RMA-2 can also assign eddy viscosity automatically at each time step or iteration based upon cell Peclet number and modeled velocity.

To improve model convergence, RMA-2 offers two wetting and drying features that remove dry cells of the mesh from the computations when they become completely dry between iterations. For habitat flow studies where the same mesh is used for a range of flow rates (from roughly median flow down to a roughly 15 percentile flow), the ability of the model to automatically eliminate dry cells from the calculation without diverging saves time and effort. The Marsh Porosity feature is used in combination with the wetting and drying feature as specified in Donnell and others (2001).

Although RMA-2 has been recently used for habitat flow studies in Texas, some limitations exist that may preclude its use on some study reaches. The RMA-2 model is limited to subcritical flow problems in reaches without steep local bed slopes. If situations violating these conditions are encountered, another more suitable hydraulic model will be used (such as FESWMS or River2D).

7 *Biology*

Biological evaluations, surveys, riparian assessments and models, and instream microhabitat and mesohabitat models will play a substantial role in identifying flow conditions needed to maintain a sound ecological environment. Specific elements will vary according to the portion of the flow regime under consideration.

For subsistence flow recommendations, biological considerations may dictate which water quality constituents (such as dissolved oxygen, temperature, and turbidity) will be of primary concern in a particular reach of river. Habitat considerations will include maintaining adequate flows so that key habitats are not dewatered or reduced to unsuitable conditions for lotic-adapted species (such as mussels, riffle-dwelling fishes, and invertebrates) or other key or imperiled species.

Base flow recommendations will rely primarily on habitat models that use habitat criteria derived from biological data to assess instream habitat (quantity, quality, and diversity) relative to streamflow. These models provide a means to identify a range of flows that provide suitable habitat conditions and allow for quantitative comparisons of different flow scenarios, such as different release schedules from reservoirs or hydropower operations.

Biological considerations, such as migration, spawning cues, and maintenance of key habitats through geomorphic processes, will play an important role in developing the high flow pulse component of the flow regime. To develop overbank flow recommendations, the Agencies will evaluate and model riparian systems and linkages between aquatic biota (such as floodplain spawning fishes) and active floodplain and channel processes. The historical flow data related to high flow pulses and overbank flows will largely determine magnitudes of flows, but the timing and duration of these types of events may be influenced by life histories of aquatic and terrestrial (riparian) communities. Conceptual models, targeted assessments, and/or available information, rather than instream habitat modeling, will be most effective for developing these flows.

7.1
HYDROLOGY AND RIVERINE ECOSYSTEMS

Because hydrology plays a substantial role in determining the composition, distribution, and diversity of aquatic communities, a central focus of instream flow studies is to relate the biology of a lotic system to its flow regime. (Bovee and others, 1998; Annear and others, 2004). Riverine biota have evolved life history strategies that correspond to natural flow regimes. Information to address flow requirements in key habitats, such as shallow water habitats, during critical time periods (spawning and rearing) is an essential element of instream flow studies.

Biological evaluations will focus on fish assemblages but may also address other vertebrates, invertebrates, or plants as study objectives dictate. Habitat and water quality requirements, life history, and other ecological factors, such as connectivity, will be assessed to provide input to habitat models and insight into the integration element. Fish are advantageous target organisms because they are relatively easy to identify; use a wide array of habitats, including flow-sensitive habitats; offer a wide range of life histories, many of which are tied to flow dynamics; are generally well studied relative to other aquatic taxa; are a good integrator of overall health of the system; and have a high public profile and commercial importance. Nonetheless, in some systems and as objectives dictate, it is likely that other focal taxa such as mussels will need to be included to ensure that the goals of the instream flow program are met. Likewise, specific information or models may need to be developed to identify flow conditions necessary to maintain riparian areas, such as hardwood bottomlands, riparian wetlands, oxbows, and other habitats.

Flow regimes largely determine the quality and quantity of physical habitat available to aquatic organisms in rivers and streams (see Bunn and Arthington, 2002). Habitat complexity or heterogeneity is a primary factor affecting diversity among fish assemblages (Gorman and Karr, 1978; Bunn and Arthington, 2002) because heterogeneous habitats offer more possibilities for resource partitioning (Wootton, 1990). Channel morphology, the sequence of riffles, pools, and other habitats, and substrate composition result from interactions of flows and watershed geology. Lotic biota respond (in terms of abundance, distribution, and diversity) to changes in physical habitat. Flow-dependent organisms, such as riverine fish, tend to show preferences for specific habitat conditions as characterized by current velocity, depth, substrate composition and distribution, and cover (Schlosser, 1982). This habitat-preference behavior is a primary assumption of habitat-based instream flow models (Annear and others, 2004). In addition to their usual flow requirements, many riverine fishes time migration, spawning, and other activities to seasonal changes in flow regimes (see Stalnaker and others, 1996). Flow regimes also influence physical and chemical conditions in rivers and streams, which, in turn, influence biological processes. For example, changes in a flow regime may result in the accumulation of fine sediments in otherwise suitable habitats, impairing the reproductive success of biota. Connectivity, the movement of energy, organic and inorganic matter, water, and biota within an ecosystem, plays a major role in riverine systems (Ward and others, 2002) and is essential to survival, growth, and reproduction of many riverine species and the maintenance and function of riparian areas (NRC, 2002).

Riparian areas are important components of river ecosystems, and riparian structure and function depend on flow regimes (NRC, 2002). Riparian areas are defined as ecotones or corridors between terrestrial and aquatic realms (Melanson, 1993) and are often the only portion of the landscape moist enough to support tree growth and survival in drier western climates (Busch and Scott, 1995). According to the National Research Council (2002), riparian areas

> are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence). Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine-marine shorelines.

Riparian areas perform key ecological functions that contribute to the health of the entire ecosystem (Wagner, 2004). They support physical, chemical, and biological processes in rivers and streams, including biogeochemical and nutrient cycling, organic matter and sediment exchange, temperature dynamics (through shading), and stabilization of streambanks. Riparian areas often have high biodiversity and biological productivity (NRC, 2002). Additionally, riparian habitats are essential for many vertebrate species and provide critical physical and biological linkages between terrestrial and aquatic environments (Busch and Scott, 1995; Gregory and others, 1991). It is estimated that 80 percent of all vertebrate species in the desert southwest depend on riparian areas for at least some part of their life cycle (Wagner, 2004).

Changes in hydrology can lead to loss of connectivity between riparian areas and stream channels, resulting in reduced diversity and altered ecological integrity (Nilsson and Svedmark, 2002). For example, reproduction and growth of riparian plant species are closely associated with peak flows and related channel processes such as meandering (Busch and Scott, 1995). Studies by Busch and others (1992) of plant water uptake in floodplain ecosystems indicate that maintaining cottonwood and willow populations depends on groundwater moisture sources, which, in turn, are closely linked to instream flows. Busch and Scott (1995) conclude that establishing and maintaining riparian plant communities are a function of the interplay among surface water dynamics, groundwater, and river channel processes. They maintain that the health of natural riparian ecosystems is linked to the periodic occurrence of flood flows, associated channel dynamics, and the preservation of base flows capable of sustaining high floodplain water tables. Additionally, dam construction, diversions, and groundwater pumping have directly or indirectly caused changes in the hydrologic and fluvial processes necessary for riparian vegetation establishment and persistence (Lytle and Merritt, 2004). Hydrologic changes contributing to the decline of riparian ecosystems as a result of dams typically include complete inundation and subsequent elimination of riparian habitat upstream of dams and changes in the frequency and magnitude of peak flows, shifts in the timing of peak flow, and changes in the rate of river stage decline downstream (Lytle and Merritt, 2004).

7.2
ASSESSMENT OF CURRENT CONDITIONS

Assessing the current biological condition of each system in relationship to instream flows and identifying key physical, hydrologic, and chemical processes and critical time periods is an important starting point for further biological studies. Data requirements include information on life history traits (such as spawning season requirements and foraging traits), environmental requirements (habitat, temperature, and dissolved oxygen), species distributions, community composition, and connectivity considerations.

Previously collected information will be assembled from several sources: 1) reports by state agencies in Texas (the Texas Parks and Wildlife Department, Texas Commission on Environmental Quality, and Texas Water Development Board or predecessor agencies) and state agency reports from Louisiana, Oklahoma, and New Mexico; 2) federal agencies (such as the U.S. Geological Survey, U.S. Fish and Wildlife Service, U.S. Army Corps of Engineers, and U.S. Bureau of Reclamation); 3) journal articles; 4) reports from river authorities and water districts (including Texas Clean Rivers Program assessments and reports); 5) university studies and museum records; and 6) other sources. To the extent possible, data compatible with spatial analysis will be organized into an ArcGIS-based tool for use in study planning and design. These previously collected data will be reviewed and analyzed as appropriate and summarized to describe current knowledge, facilitate development of conceptual models, and identify data gaps. Field surveys (see Section 7.2.2 for example) will be conducted to address data gaps and identify trends in assemblage dynamics. Further, these initial surveys will facilitate the development of study goals, objectives, and indicators (see Section 5.2.2); sampling strategies; identification of taxa of interest;

and delineation of study boundaries and intensive study areas.

7.2.1
Instream Habitat Surveys

For each study reach, GPS units will be used to delineate mesohabitats according to the following characteristics:

- **Pool**—flat surface, slow current, usually relatively deep
- **Backwater**—flat surface, very slow or no current, usually out of main current
- **Run/Glide**—low slope, smooth, unbroken surface
- **Riffle**—moderate slope, broken surface
- **Rapid**—moderate to high slope, very turbulent (for example, a boulder field)
- **Chute**—very high velocities in confined channel

If the mesohabitat can be further discriminated, it will be assigned a qualifier for relative current speed and depth, using “fast” or “slow” for current velocity and “shallow’ or “deep” for depth. Notes on location and density of woody debris and other instream cover, unique habitat features (such as a unique outcrop), and substrate composition will be taken. Measurements of current velocity and depth will be take to facilitate developing objective criteria for defining mesohabitat types in each sub-basin study. This preliminary evaluation of the spatial mosaic of habitat types within each reach will offer guidance on development of study boundaries, stratification strategies for sampling, and other study design factors. These mesohabitat surveys should be performed when flows are at or below the median flow and habitat features are relatively easy to evaluate. Standardized field guides and sampling protocols will be provided to field crews in order to maximize the accuracy and repeatability of habitat data collection.

7.2.2
Fish Surveys

For each study reach, identifiable mesohabitats will be sampled for fish using the most appropriate gear, such as seines or electrofishers. Sample reach lengths will be based upon a multiplier (40 times the mean wetted width) with a maximum of 1,000 meters (about 0.6 miles) or one full meander wavelength (whichever is longer). Physical measurements will be made in association with each sampling event (such as each seine haul) and will include current velocity, depth, substrate composition and embeddedness, instream cover (large woody debris, boulders, undercut banks, macrophytes, and velocity shelters), and other measurements as deemed necessary. Notes on climatic conditions and mesohabitat typing will be recorded. In addition to providing data on relationships between mesohabitats and fish presence and abundance, this information will facilitate the design of appropriate sampling strategies for collecting quantitative microhabitat utilization data (see Section 7.3.1). It will also provide data on current conditions for monitoring and verification and allow appropriate biological indices to be calculated. Released fish will be identified, measured, photodocumented, and examined for disease and other anomalies. Voucher specimens will be preserved in 10 percent formalin for identification quality control checks. In all cases, fish collecting will proceed as long as additional species are being collected.

Boat electrofishing (900 seconds minimum) will focus on habitats too deep or swift for effective backpack or seine sampling (such as pools and fast runs). An attempt will be made to collect all shocked fish and special effort will be exerted to collect fishes that may be rolling on the bottom. When a particular habitat has been thoroughly sampled, electrofishing will pause to enumerate the collected fish. Site information, personnel, and output settings will be recorded. Electrofishing time and species enumeration will be recorded for each habitat type sampled.

Backpack electrofishing (900 seconds minimum) will focus on areas shallow enough for effective sampling (such as riffles and shallow runs). If necessary, seines placed downstream of the backpack crew can be used to assist in fish collection. Fishes collected from each habitat sampled will be processed independently. Site information, personnel, and output settings will be recorded. Electrofishing time and species abundance will be recorded for each habitat type sampled. Fifteen minutes is the minimum trigger time for all electrofishing methods combined.

Seining (at least 10 effective seine hauls) will be conducted in various habitats using a variety of seines and seining techniques (riffles kicks) in order to complement shocking efforts. Examples of commonly used seines include a 9.1 meter x 1.8 meter x 7.6 centimeter (30 feet x 6 feet x 1/4 inch) mesh seine for sampling pools and open runs and a 4.6 meter x 1.8 meter x 5.7 centimeter (15 feet x 6 feet x 3/16 inch) mesh seine for sampling riffles, runs, and small pools. All seines will be constructed of delta weave mesh with double lead weights on the bottom line. Site information and personnel will be recorded. Fishes collected from each seine haul will be processed independently.

7.2.3
Aquatic Invertebrate Surveys

For each study reach, three types of samples will be collected: kick net, woody debris (snag), and hand picked. Physical habitat data (see previous section) may also be collected in association with aquatic invertebrate surveys. For benthic samples, nine kick-net samples will be taken for 20 seconds each using a large, tapered kick net (600 micrometer mesh, 330 x 508 millimeter frame size, or similar net). Sampling will occur over an area approximately 1 meter by 0.5 meter (3.3 feet by 1.65 feet) directly in front of the collecting net. Three samples each will be collected from each major habitat present (riffle, run, and pool) in the study reach, with sampling to occur from downstream to upstream. One of each sample type will be taken alternatively from the right, left, and middle portion of the stream channel of each habitat. For riffles and runs, the streamflow will carry dislodged invertebrates into the collection net. For pool samples, where water velocity is minimal, the collector will swirl the net in a circular fashion through the area being kicked to maximize the collection effort. Bulk benthic samples will be washed in a standard wash bucket (600 micrometers or less) to eliminate fine silt and sand. Remainders of the bulk benthic samples will be individually preserved in at least 70 percent isopropyl alcohol. The preservative will be replaced with fresh isopropyl alcohol after 12 hours to ensure proper preservation.

Woody debris will be collected in amounts sufficient to fill a 1-gallon (3.8 liters) collection jar and then preserved with at least 70 percent isopropyl alcohol. The debris will be collected from throughout the study reach and include well-seasoned and highly-reticulated wood with irregular or rough surfaces. Green wood or very small diameter (less than 2 centimeters or ¾ inch) pieces will be avoided.

Hand-collected sampling consists of collecting miscellaneous aquatic invertebrates from stones, woody debris, and other substrates as appropriate. Special effort will be made to collect a wide variety of immature mayflies to aid in identifying specimens collected in benthic samples. Specimens collected will be preserved in at least 70 percent isopropyl alcohol. Miscellaneous invertebrates will be collected from throughout the study reach. Mussels (including shells) and macrocrustaceans will also be collected if observed.

Benthic samples will be rinsed through a sieve (600 micrometers or less), using tap water to remove fine sediments. Sample contents will be sorted completely (in portions as necessary) in white enamel or plastic pans with all invertebrates stored in individual vials and preserved with at least 70 percent isopropyl alcohol. Specimen vials will be labeled to show collection location, type of habitat, date collected, and collector. Snag samples will be rinsed into a white enamel or plastic pan and the contents collected by rinsing through a sieve (600 micrometers or less) using tap water. Individual pieces of woody debris will be carefully examined to ensure that all attached invertebrates have been removed. Invertebrates removed from the snag samples in the laboratory will be collectively preserved in at least 70 percent isopropyl alcohol. Snag material will be measured volumetrically (cubic centimeters) in order to obtain an estimate of the amount of surface area sampled. This can be accomplished by adding the woody debris to a large container partially filled with a known volume of water and then measuring the volume of water displaced.

Specimens will be identified to the lowest possible taxonomic level using appropriate references (Pennak, 1989; Merritt and Cummins, 1996). For sample analysis, the following metrics (TNRCC, 1999) will be calculated, as appropriate:

- Taxa richness
- Ephemeroptera-Plecoptera-Trichoptera ratio
- Ratio of Ephemeroptera-Plecoptera-Trichoptera and Chironomidae abundances
- Percentage Cheumatopsyche of total Trichoptera
- Percentage contribution of dominant taxon
- Percentage exotic species
- Ratio of scraper and filtering collector functional feeding groups
- Benthic densities: number of specimens per square meter
- Snag samples: number of specimens per cubic centimeter

A benthic Index of Biotic Integrity may also be calculated.

7.2.4
Riparian Area Surveys

Because hardwood bottomlands and other wetland systems (such as oxbows) are important riparian habitat types, they warrant detailed assessment. Previously collected data related to the location of important riparian features will be compiled from maps, GIS sources, aerial photography and satellite imagery, and other sources. Reconnaissance-level data will be gathered to assess areas that need additional investigation (such as modeling or extensive data collection). Riparian areas will be evaluated in terms of connectivity to the river channel within a biological and hydrological context.

The following methodology will be used to determine the extent, hydrologic requirements, and connectivity of riparian areas associated with sub-basin instream flow studies.

Extent and identification of riparian area distribution

There are several integral factors that must be assessed in order to determine the status and condition of riparian ecosystems. As a critical first step, identifying and distributing riparian area extent will be accomplished by combining information from several different approaches: remote sensing, topography, soils, hydrology, and vegetative sampling/ground-truthing. This information must be correlated in order to determine overall riparian ecosystem status and management requirements. The methodology to address these factors in determining riparian area distribution follows.

Remote sensing

Although there is not a consistent methodology for monitoring riparian area trends, remote sensing is increasingly being used as an important landscape assessment of riparian community composition and distribution (NRC, 2002). To form a base map for the distribution of riparian habitat along the river reaches in question, Landsat thematic mapper imagery (ETM+) from 1999 and 2001 will be compiled. For a more detailed interpretation of riparian habitat, Digital Orthographic Quarter Quadrangles from 1995 and 2004 will then be assembled. Vegetation and landscape features will be digitized and converted into shape file layers using ArcGIS. These shape files will be overlaid on the ETM+ base map.

Topography

U.S. Geological Survey topography data (Digital Elevation Models, Triangulated Irregular Networks) will be compiled and combined with the ETM+ base map to produce a vertical representation of the river reach being studied. These data will also be used when determining the hydrologic requirements for maintaining a healthy riparian ecosystem.

Soils

Riparian areas have been disturbed by agricultural practices, logging, land clearing, and other factors, which can make classifying riparian areas by vegetative indicators difficult because native indicators may no longer be present. Therefore, soil characteristics derived from data in the 1:24,000 Soil Survey Geographic Database will also be used in assessing riparian area extent. Riparian soils types will be identified and digitized as an additional layer on the ETM+ base map to further delineate riparian area extent.

Hydrology

Hydrology layers from the U.S. Geological Survey 1:24,000 data will be assembled and correlated to the soils, topography, and riparian vegetation classification layer on the base map.

Vegetative sampling/ground-truthing

Vegetation community types delineated from the above remote sensing methods will be ground-truthed (field verified) and sampled for specific data on species structure and composition, age class, percent canopy cover, and other related factors. These results will be correlated to important riparian functions, such as streambank stabilization, temperature dynamics, and nutrient cycling.

Determining hydrologic flow requirements necessary for maintaining riparian areas

When determining flow requirements for maintaining healthy riparian ecosystems, understanding the characteristics of natural flow patterns (frequency, magnitude, duration, timing, and rate of change) is crucial (NRC, 2002). However, a standard methodology for determining overbank flow requirements of riparian ecosystems has yet to be developed. Therefore, a model will be developed using three components: U.S. Geological Survey topography data and hydrologic boundary files for delineating watersheds and NEXRAD rainfall data (over a 50-year period) to determine peak discharges. Once the model has been constructed, the results will be correlated to the seed dispersal and germination time frame of the dominant native vegetation type found within the riparian plant communities (or linked to life histories of other taxa, such as fishes that use riparian areas) to determine the duration, magnitude, and timing of overbank flow recommendations.

Connectivity of riparian ecosystems

To further elaborate on the importance of hydrology to the ecological integrity of riparian systems, Tabacchi (2005) maintains that the gradient of inundation may be the most objective and strongest indicator of riparian influence, with the gradient of inundation by surface waters as an obvious parameter of influence. He cites Gold and Kellogg (1997) who point out that water table dynamics should be recognized as a full component of a riparian model. By considering groundwater and surface water dynamics as main controls of the riparian ecosystem, Tabacchi (2005) developed a model that delineates an indicator variable from hydrological data series. This model is illustrated in Figure 7-1 in which the lower, gray line depicts the long-period probability of inundation by groundwater as a function of elevation. The upper, black line represents the long-period probability of inundation by groundwater as a function of river water level. The Unsaturated Zone of the water table and the Flooded Zone are also shown. The Transitional Water Table Distance is the physical difference in elevation between the inflexion points of the two curves. The riparian zone is defined as the common domain of the 95 percent confidence intervals for the two cumulative distribution functions. Transition curves can be asymmetric. This model defines the space of interaction between nonatmospheric water and substrate as a gradient of probability of inundation of both superficial area (Flooded Zone) and unsaturated groundwater zone (Unsaturated Zone). Swamp zones occur when the Unsaturated Zone overlaps the Flooded Zone. The Transitional Water Table Distance defines the coupling between surface and groundwater. An important attribute of this model is that it can be coupled to a Digital Elevation Model to produce a map of the riparian zone.

One way to test this model is to sample groundwater depth in the sites selected for vegetative sampling/ground-truthing and couple it with surface water data to produce the probability of inundation curve. This curve will be compared to the ETM+ base map produced through the above procedures.

7.3
INSTREAM HABITAT

Most instream flow studies model habitat availability in response to discharge with the assumption that physical and hydraulic variables determine the spatial distribution of aquatic organisms (Bovee and others, 1998; Annear and others, 2004). Habitat availability is used as a surrogate for empirical information relating antecedent flow patterns to specific life-history events or flow-dependent biological responses at the individual, population, or community level. These relationships are difficult to develop because they are resource and time intensive. Resource limitations and time constraints (studies are expected to be completed in three to five years) mean that data cannot be collected at all flows; additionally, high flows present practical difficulties and safety hazards. Thus, representative flow windows will be selected for sampling. Habitat modeling provides a useful tool to simulate conditions that time or resources preclude measuring. However, modeling that involves making extrapolations beyond the conditions sampled is fraught with uncertainty, and care will be taken to ensure assumptions are documented. Models also tend to simplify complex ecological processes. Adaptive management has been suggested to address such uncertainty in instream flow management and restoration (Castleberry and others, 1996; see Richter and others, 1997).

Two complementary approaches to assessing instream habitat are discussed. The first is an assessment of the relationships between instream microhabitat and streamflow and the second is an assessment of habitat heterogeneity and streamflow.

7.3.1
Quantity and Quality of Instream Microhabitat

One focus of the biological study element is to assess the quantity and quality of instream microhabitats used by lotic organisms and relate that utilization to streamflow. Several steps are involved in this assessment:

- Sample assemblages and measure habitat conditions
- Calculate habitat suitability criteria
- Integrate criteria with simulations of instream habitat over a range of flows
- Develop habitat time series

Sample assemblages and measure habitat conditions

Sampling should be conducted in a quantitative manner to relate species presence and density to microhabitat conditions. To develop accurate and unbiased data, several questions must be considered:

1. **At what flows should data be collected?** Data should be collected over a range of streamflows so that the full complement of potential habitats are available and thereby provide choice of biota. Sampling over a range of flows may also minimize the influence of food availability, competition, and predation on habitat selection (Power, 1984; Orth, 1987).
2. **When should data be collected?** Habitat use can vary with life stage, season, and life-history events, such as spawning or migration, and diurnally (nighttime versus daytime; Johnson and Covich, 2000). Shift in habitat use can be accounted for by incorporating temporal aspects into study design, such as seasonal and diurnal sampling protocols.
3. **Which taxa will be sampled in each study?** Taxa will be determined

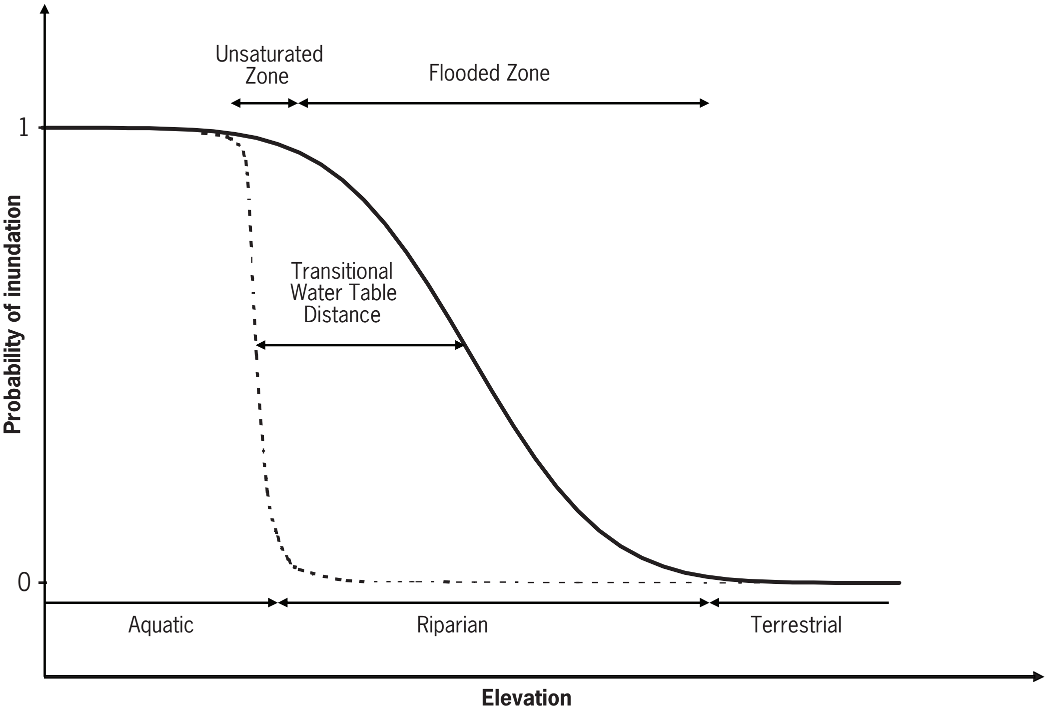


Figure 7-1. Hydrological representation of the riparian zone as a sum of transitional gradients (modified from Tabacchi, 2005).

during the study design phase and will be based on literature review and empirical information collected during initial sampling.

4. **What variables will be measured to describe habitat conditions?** Most habitat-based instream flow studies focus on current velocity, depth, substrate, and instream cover (Bovee and others, 1998). Other variables may need to be addressed depending on taxa. For example, near-bed hydraulics (shear stress) has been used to relate macroinvertebrate and mussel distributions and, in some cases, densities to microhabitat conditions (Gore and others, 2001; Hardison and Layzer, 2001).

Many approaches for collecting quantitative data on microhabitat utilization have been developed and used in instream flow assessments. However, given the diversity in characteristics among rivers, one approach will not be suitable for all systems studied, and appropriate collecting techniques will vary with habitat conditions and specific taxa. In Texas, “bio-grids,” composed of equal area (10 square meters or 33 square feet) sampling cells formed with ropes and taut lines, have been used to develop suitability criteria for fishes in the Colorado River (Mosier and Ray, 1992) and for aquatic macrophytes in the San Marcos River (Saunders and others, 2001). Within each cell, biota are sampled and habitat characterized. Bio-grids are used for sampling in shallow habitats (such as riffles, runs); however, they can be modified to facilitate boat electrofishing by converting cells into sampling lanes. Stratified random sampling designs have been used across the country from trout streams in the west to species-rich rivers in the southeast. Many fish sampling tools are at the disposal of biologists, including backpack and boat-mounted electrofishers, prepositioned area electrofishers, and various seines. With the exception of boat electrofishing, these techniques are limited to relatively shallow habitats (about 1 meter or 3.3 feet deep); high current velocities may also preclude sampling in some locations.

Collecting habitat use data of macroinvertebrates attempts to be more quantitative than initial invertebrate surveys and may, therefore, require equal-area benthic samplers. These quantitative samplers can only be effectively deployed in wadable areas of rivers and streams. Gore and others (2001) recommends collecting between 25 and 50 random samples along transects located in riffles since these are key habitats likely to be most affected by reduced flows. Direct visual observations may work well for some taxa (such as mussels) in some rivers. In addition, standard hemispheres (Statzner and Müller, 1989; Hardison and Layzer, 2001) can be used to estimate shear stress on stream bottoms and can be used as surrogates for invertebrates, thus avoiding long sample processing times and identification issues associated with macroinvertebrate habitat utilization studies.

A primary assumption of habitat-based instream flow models is that flow-dependent species such as riverine fish tend to demonstrate preferences for specific habitat conditions (Annear and others, 2004). For example, many darter species prefer high velocity, shallow habitats over clean cobble and gravel substrates. In addition, instream cover may provide shelter from current or predators and exists in many forms, including undercut banks, macrophytes, boulders, and large and small woody debris. Some species may directly associate with particular instream structures during different life stages or life-history events. Large woody debris provides sites for macroinvertebrate colonization and may be relatively abundant in some streams. To locate and characterize microhabitat conditions within each biological sample unit, the following measurements will be made:

- Mean column velocity, using a wading rod and current velocity meter
- Water depth, using a wading rod
- Substrate composition, using a modified Wentworth scale (Bunte and Abt, 2001)
- Embeddedness, a measure of the degree that interstitial spaces surrounding substrate (large gravel and cobble) are occupied by smaller substrates like silt and sand
- Instream cover, such as woody debris, macrophytes, velocity shelters formed by objects and substrates, and undercut banks
- Mesohabitat type (see Section 7.2.1),
- Other hydraulic variables (such as shear stress) as required by study design
- Location information, using position averaging GPS units.

An attempt will be made to sample homogeneous patches of microhabitat, but in some sample units it may be necessary to average multiple measurements to characterize microhabitat conditions accurately.

In some cases, it may be necessary to identify target species that have key habitat requirements (such as a shallow habitat for spawning) and critical time periods (for example, limited spawning season). Species that use key habitats may be most important because these habitats are substantially affected by reduced streamflows. For example, many darter species in Texas solely use riffle habitats, which, as flows decline, become exposed or unsuitable (insufficient depth or current velocity) for occupation. Further, darter species have specific critical time periods for spawning, which generally occur during the spring months when streamflow conditions are higher. Thus, obtaining information on microhabitat-utilization data on riffle-dwelling species may be most important in some river segments.

Calculate habitat suitability criteria

Many approaches have been used to calculate habitat suitability criteria of fish (Bovee, 1986; Vadas and Orth, 2001) and macroinvertebrates (see Gore and others, 2001). Utilization criteria are calculated based on relative proportions of habitat used by target species or guilds, and preference criteria account for the availability of habitat conditions. The concept of nonparametric tolerance limits has been applied to developing suitability criteria for instream flow studies (Bovee, 1986; Mosier and Ray, 1992). These tolerance limits delineate a range of habitat conditions used by a proportion of the sampled population. Binary criteria indicate an on-off switch and dictate that habitat conditions are either completely suitable or not, and univariate criteria (weighted) represent a range of suitabilities given different habitat conditions in one environmental variable. Hydraulic criteria, such as the Froude number and shear stress, may be useful (Jowett, 1993).

Recent instream flow evaluations of complex and species-rich communities have used habitat guilds or species with similar habitat utilization patterns to simplify assessments (Leonard and Orth, 1988; Aadland, 1993; Mosier and Ray, 1992). Balancing instream flow requirements for a large number of target species simultaneously is problematic. Guilding provides a means to reduce the number of response curves involved in integration but also reflects an assemblage-based approach to addressing instream flow requirements, thereby avoiding stochastic factors (biotic and abiotic) that influence individual species (Vadas and Orth, 2000). Perhaps most important, mesohabitats can be defined using biological criteria derived from habitat guilds (Leonard and Orth, 1988; Aadland, 1993; Bain and Knight, 1996; Vadas and Orth, 2000). Statistical approaches to define guilds include clustering (Aadland, 1993) and multivariate (Vadas and Orth, 2000) methods, many of which are readily available in statistical software packages (such as SAS). However, the approach used to derive criteria for habitat guilds may vary by basin or sub-basin study area; it is also possible that habitat guilds can be transferred from one study area (or basin) to another (NRC, 2005), but statistical methods would need to be found or developed to test transferability (see Freeman and others 1999 for a discussion of transferability of suitability criteria). Peterson and Rabeni (1995) advocate use of fish guilds for stream fish community studies and also indicate the use of guilds would increase the cost efficiency of a study. It would reduce sampling efforts while obtaining a reasonable level of precision. Further, it may also be necessary to generate habitat suitability criteria for individual target species, particularly those with specialized habitat requirements (such as fluvial habitat specialists) or specific environmental requirements at critical times. Imperiled species may also receive separate attention. For example, Mosier and Ray (1992) recommended flow regimes in the Colorado River but also included provisions for increased flows to facilitate spawning conditions for the *Cycleptus elongates*, blue sucker.

Integrate habitat suitability criteria with simulations of instream habitat over a range of flows

Habitat-discharge relationships will be developed by integrating habitat suitability criteria for target species and guilds with models of instream habitat simulated over a range of flows. These relationships will provide information to identify subsistence and base flows needed to support assemblages and key species. This study component is discussed in detail in Section 10.2.1.

Develop habitat time series

Habitat time series will be produced using habitat-discharge relationships and hydrologic time series (Bovee and others, 1998). A necessary component of this analysis is hydrologic time series at temporal scales (such as daily and monthly) appropriate for the taxa of interest. Hydrologic time series (see Chapter 6) can be derived for natural conditions, historical conditions, and proposed conditions after project implementation. Habitat time series are useful for evaluating potential impacts to habitat conditions through time, resulting from hydrologic alteration. Time series provide a method to link temporal aspects of life history and ecology with alterations to flow regimes (Stalnaker and others, 1996). The timing, duration, and amount of habitat can provide insight into potential habitat bottlenecks (Bovee and others, 1994).

7.3.2

Habitat Heterogeneity

A complementary assessment will relate habitat heterogeneity with streamflow. Riverine habitat heterogeneity (or diversity or complexity) plays a strong role in supporting diversity in aquatic assemblages (Gorman and Karr, 1978; Schlosser, 1982; Poff and Ward, 1990; Reeves and others, 1993; Bunn and Arthington, 2002; Robinson and others, 2002). The relationship of diverse assemblages to diverse habitat is generally accepted (see Ward and Tockner, 2001), but other factors such as predation, competition, and disturbance regimes may confound assemblage-habitat relationships (Poff and Ward, 1990; Robinson and others, 2002). Lotic ecologists are integrating the themes of landscape ecology into riverine ecology (Fausch and others, 2002; Ward and others, 2002; Wiens, 2002), and this may have important implications in assessing instream flow requirements.

Spatially explicit habitat models derived from GIS systems and two-dimensional hydrodynamic models will yield the types of information regularly used in landscape ecology to evaluate spatial heterogeneity. Techniques of landscape ecology have been applied successfully to the study of riverine habitat (Bovee, 1996; Hardy, 1998; Gergel and others, 2002). Software such as Fragstats enables analysis of spatial patterns and characteristics, such as patch size (of habitat types), number and density, diversity and dominance of patch types, and shape of patches and their edges (McGarigal and Marks, 1995; Johnson and Gage, 1997).

An assessment of how habitat heterogeneity changes with respect to streamflow will be conducted. The first step is to classify instream habitat at an intermediate scale. Jowett (1993) used Froude numbers to distinguish pools and riffles. Vadas and Orth (1998) developed hydraulic criteria to classify mesohabitat types (riffles, runs, and pools) in warmwater streams (less than 50 meters or 165 feet wide). These criteria may be transferred to other streams but could require modification if used in larger rivers and streams in Texas. A second approach classifies mesohabitats (shallow, margin habitat) based on biological criteria using fish (Bain and Knight, 1996; Bowen and others, 1998; Freeman and others, 2001) or benthic communities (Pardo and Armitage, 1997). The National Research Council (2005) recommended exploring the use of habitat guilds to develop objective criteria for designating mesohabitats. Using biological criteria to classify mesohabitats is intuitively a biologically sound approach since it is tied to the use of mesohabitats by lotic organisms. However, the specific approach used in each basin study will depend on the habitat characteristics of the river basin and biological communities. The second step is to model how mesohabitat changes with streamflow, using a spatially explicit habitat model (see Chapter 10). The third step is to characterize the resultant habitat mosaic at each flow level, using landscape metrics (patch size and diversity). Bowen and others (2003) conducted a spatial analysis of area, number, and density of shallow water patches in the Yellowstone and Missouri rivers to assess the effects of flow regulation. Combining these relationships with hydrologic time series can then produce time series of various metrics that describe habitat heterogeneity. The result of the assessment is specific relationships between flow and habitat heterogeneity through time, which can be used in a complementary assessment of instream habitat-discharge functions.

8 *Physical Processes*

Streams and rivers transport not only water but also sediment. Water carries silt, sand, gravel and other material from where it is eroded in the watershed to where it is deposited in the river channel, floodplain, or terminal delta. Sediment transport and deposition processes directly link a river to its watershed and riparian areas and sculpt the physical features of the channel and floodplain. In combination with the hydrologic flow regime, these physical features form the habitats to which all biological elements in the river ecosystem have adapted and become dependent. As a result, physical processes, which vary over a wide range of spatial and temporal scales, play an important role in developing and maintaining a sound ecological environment for river systems.

If physical processes are ignored or poorly understood when setting instream flows, the long-term health of the river system cannot be maintained. In order for instream flow recommendations to be effective, the desired physical features of a river must be maintained. For most river systems, base flows are not sufficient to maintain these features. An appropriate sediment regime and higher flow components are also required. Management of the Trinity River in northern California illustrates this point. As described by Trush and others (2000), managers selected instream flows downstream of Lewiston Dam to provide "ideal hydraulic conditions" for salmon habitat. Unfortunately, providing "ideal" base flows without considering sediment and other flow regime components required to maintain physical habitats had unintended consequences. Trush and others (2000) describe the effects:

> The river's complex alternate bar morphology was quickly transformed into a smaller, confined rectangular channel now unable to meander. Floodplains were abandoned. Cumulatively, this flume-like morphology and floodplain isolation greatly reduced habitat quantity and complexity important to numerous aquatic and riparian species. Salmon populations were immediately and significantly affected.

In the Texas Instream Flow Program, the importance placed on physical processes will vary for each instream flow component. Subsistence flows generally have little effect on the physical features of a river system. The effects of base flows are limited to working on the condition of the bed forms. However, during studies to develop base flow requirements, an assessment of channel bed forms and banks will assist biologists in identifying important physical habitats. Investigating these habitats will highlight desired conditions, such as sediment composition of transverse channel bars and depth of scour pools. Appropriate high flow pulses and overbank flows required to maintain these conditions can then be developed.

High flow pulses play an important part in developing and maintaining in-channel habitats. The ability of modest, but more frequent, high flow events to move more sediment over time than larger, infrequent events is well documented (Wolman and Miller, 1960) for humid climates. In arid or semihumid climates, channel maintenance depends more on larger, infrequent events (Wolman and Gerson, 1978; Huckleberry, 1994). Although smaller in magnitude than overbank flows, high flow pulses occur more frequently and, therefore, play a more active role in sculpting in-channel habitats. Geomorphic studies will assess the active channel processes responsible for developing physical habitats. These processes may include pool scouring and sediment sorting, in addition to creating specific bed forms or specialized channel habitats such as undercut banks. The Agencies will develop sediment budgets describing the sources and deposition of sediment in the river system. These budgets are used to identify sediment limitations or excesses that may affect the ability to achieve desired outcomes. The ability of current and alternative sediment and hydrologic regimes to adjust channel features can then be assessed. Recommendations for high flow pulses will take into consideration seasonality, magnitude, frequency, duration, and rate of increase and decrease.

Overbank flows provide critical functions in support of river ecosystems. These include developing and maintaining floodplain habitats, providing nutrients and sediments to riparian areas, transporting organic debris to the channel, and preventing channel constriction due to encroaching vegetation. Geomorphic field studies will determine active floodplain areas and assess active floodplain and channel processes. Hydraulic modeling of the extent of inundation (described in Section 6.2) and results of riparian area surveys (described in Section 7.2.4) may assist in developing appropriate overbank flow recommendations. Geomorphic assessment of overbank flow and high flow pulse behavior will also analyze bank stability. The duration and magnitude of flows will be adjusted in order to reduce adverse impacts to channel banks.

Two factors make incorporating an understanding of physical processes into the instream flow studies difficult. First, Texas' rivers experience a large range of climatic and geologic conditions and, therefore, the function and behavior of their physical processes vary greatly. As a result, geomorphic studies need to be tailored to the specific sub-basin being investigated. Second, the lack of geomorphic data for Texas' rivers is problematic. Studies can describe current conditions by collecting data related to processes on each river. However, without previously collected data, past conditions cannot be understood and predictions of the future response of a river are less accurate. To correct this situation, a monitoring program that collects geomorphic data for major rivers will be required.

8.1
PHYSICAL PROCESSES OF RIVERS

Sediment transport processes begin with the erosion of soil, rock, and organic material in the watershed. This material is then transported by surface runoff to a stream channel. Total sediment load in the channel consists of mineral and organic matter that is suspended, float load that is fine sediment and buoyant organic material, and bed load composed of coarse material moving along the channel bottom. The rate of sediment transport through the system depends on the sediment supply and the river's ability to transport that supply. The quantity and type of sediment material determines river channel stability, slope, and geomorphic features, such as the presence of sand or gravel beds.

Because sediment movement is the process that creates and maintains important physical habitats, it is crucial to the ecological health of a river. For example, riffles in alluvial rivers may provide necessary spawning areas for fish. If proper timing, pattern, and velocity of flow are not maintained, algal growth and accumulation of fine mineral material may occur in riffle areas. This result, in turn, may impair the reproductive success of biota by impeding the movement of oxygen through the substrate.

The physical laws that govern sediment transport in streams and rivers can be expressed by the following formula (Lane, 1955):

$$Q_S \times D_{50} = a \times Q \times S$$

This equation relates bed load discharge (Q_S) to stream discharge (Q) in terms of the median particle size of bed material (D_{50}), channel slope (S), and a proportionality constant (a). Stream power, a term often used to discuss the transport capacity of a stream or river, is defined as the discharge times the channel slope times the specific weight of water and is proportional to the right hand side of Lane's equation. If the discharge in a river is changed, the stream power is also changed. Lane's equation demonstrates that such a change would be accompanied by a change in the sediment discharge or the particle size pattern or some combination of these two variables.

As predicted by Lane's equation, rivers do adjust to the relative inputs of sediment and water. The river's planform, bed slope, flow depth, flow velocity, and shear stress respond to changes in input rates of water and sediment and the grain size of sediment supplies. For example, if there is an increase in sediment load while the flow rate remains constant, the channel bed aggrades in a location near the sediment input point. Conversely, if discharge (and thereby transport capacity) increases without an increase in sediment load, channel widening or scouring may occur in order to decrease the channel slope.

The energy/sediment signature of a river can be seen on the landscape of its fluvial valley. The active floodplain is a river system's major landscape feature and is maintained by the present-day discharge and sediment transport mechanisms, which are driven by the present-day climate. After a large disturbance such as a major flood, it may take several years for a floodplain to regain a shape and form similar to its original landscape. Lateral migration of the channel can account for much of the deposited sediments in a floodplain. Vertical accretion and the attachment of river islands to one bank or the other may also help to build the floodplain.

River characteristics and behavior vary across Texas based on several factors. These include bed material, flashiness, flood dominance, climate/geologic region, and groundwater/surface water interactions. Difference in bed material is responsible for much of the variation in characteristics and behavior observed from one river basin to another. Knighton (1984) provides a simple classification of rivers based on bed types (Table 8-1).

Brussock, Brown, and Dixon (1985) found that in Texas, riverbed type varied along the length of rivers, from upstream to downstream location. They classified regions in Texas as midcontinental, eastern Coastal, or ephemeral and character-

Table 8-1. Classification of riverbed types.

Class	Type	Character
Non-cohesive	Sand	Composed largely of sand-sized material (this size is transported over a large range of discharges and called "mobile" or "live" bed)
	Gravel	Composed of gravel or small cobble material transported at high discharges
	Boulder	Composed of large cobbles and boulders that are moved by infrequent large flows
Cohesive	Silt/Clay	Composed mainly of silt and clay with degree of cohesiveness related to the amount of clay
	Bedrock	Composed of no unconsolidated material

Source: Adapted from Knighton (1984)

ized the beds of rivers for each region. The midcontinental region has rivers that are gravel bedded in their extreme upstream areas, slowly change to sand bedded in their middle reaches, and start out with sand beds and change to gravel beds in the lower reaches. Eastern coastal region rivers have a sand bed throughout their lengths. The ephemeral region is generally the areas of West Texas, the High Plains, Rolling Red plains, Edwards plateau, and part of the Rio Grande plain. Rivers and streams in this region are similar to those in the midcontinental region, but small- and mid-sized streams are dry most of the year.

The beds of rivers are typically permeable to water, which can flow into or out of the streambed and banks depending on local conditions. Water accumulation or depletion can be determined by measuring the river discharge and groundwater level from wells near the channel. These interactions are important to the channel and indirectly influence the active processes of the channel. Because of the increasing use of groundwater in some regions, there is a need for better understanding of river/groundwater exchanges in parts of the state.

8.2

HUMAN IMPACTS ON PHYSICAL PROCESSES OF RIVERS

All human activities that affect sediment loading or discharge have the potential to impact the physical process of a river segment in variable and complex ways (Williams and Wolman, 1984; Collier and others, 1996; Friedman and others, 1998; Graf, 1999; Brandt, 2000; Graf, 2001; Wohl, 2004). River segments can be classified according to the impact of human activities on their geomorphic processes (Table 8-2).

The Federal Interagency Stream Restoration Working Group (1998) provides a list of human activities that may affect watershed processes, including land use changes, overgrazing, clearing of riparian vegetation, removal of woody debris from channels, channelization, streambank armoring, water withdrawals, and construction of trails, roads, dams, and levees. Table 8-3 lists possible changes in channel characteristics due to changes in flow and sediment discharge associated with some of these activities.

Damming rivers can have significant effects on natural geomorphic processes. Petts (1979) found there were generally two major changes that occur downstream of dams. One was a reduction of peak flows by amounts ranging from 25 to 75 percent. The other was a marked decrease in sediment discharge, especially for those reaches immediately downstream of a dam. Both of these changes affect the pattern of erosion and deposition and consequently cause alterations in stream channel characteristics. These changes and their associated alterations in stream channel characteristics are shown in the two, far-right-hand columns of Table 8-3.

The impact of a dam on a river's sediment discharge regime is directly related to the reservoir's sediment-trapping efficiency. As shown in the following formula, sediment-trapping efficiency can be estimated from the reservoir capacity to inflow ratio (Brune, 1953; Verstraeten and Poesen, 2000).

$$E = 100\left(0.97^{0.19^{\log C/I}}\right)$$

In the equation, E is the sediment-trapping efficiency in percent; C is the total reservoir capacity in units of volume, and I is the mean annual inflow in the same units of volume as the reservoir capacity. The sediment-trapping efficiency of reservoirs can be as high as 99 percent (Williams and Wolman, 1984). As a result, the physical processes of rivers downstream of dams can be greatly impacted by the loss of trapped sediment. Effects will extend downstream of the dam until the missing sediment is resupplied by the tributaries, banks, or channel of the river.

The only fail-safe way to determine

Table 8-2. Geomorphic "naturalness" classification of river segments.

Channel type	**Completely natural**	**Essentially natural**	**Partially modified**	**Substantially modified**	**Mostly modified**	**Essentially artificial**	**Completely artificial**
% Change	0	<10	<10	10 to 50	50 to 90	90 to100	100
Pattern, cross section, materials	No evidence of human activities	No evidence of human activities	Altered patterns or sediment	Altered patterns or sediment	Altered patterns or sediment	Altered patterns or sediment	Completely engineered
Description	Completely undisturbed	Minor modification of flow and sediment	Obvious modification of flow and sediment	Major modification of flow and sediment	Major modification of flow and sediment	Largely artificial channel	Channel completely determined by design
Minor landform	Same as before humans	Altered or changes in sediment	Altered or changes in sediment	Altered or changes in sediment	Altered or changes in sediment	Altered or changes in sediment	Altered or changes in sediment
Example				Upper Guadalupe River	Guadalupe River (IH-35 to IH-10)	Bray's Bayou, Houston	North & South Sulphur rivers

Source: Adapted from Graf (1999)

Table 8-3. Potential alterations in channel characteristics due to changes in transport variables.

	Change in transport variable							
Transport variable	Q	Q	Q_S	Q_S	Q, Q_S	Q, Q_S	Q, Q_S	Q, Q_S
Change	+	-	+	-	+,+	-,-	+,-	-,+
Potential alteration in channel characteristics								
Width	+	-	+	-	+	-	+ or -	+ or -
Depth	+	-	-	-	+ or -	+ or -	+	-
Width-to-depth ratio	+	-	+	-	+	-	+ or -	+ or -
Meander wavelength	+	-	+	-	+	-	+ or -	+ or -
Bank full area								
Sinuosity			-	+	-	+	+	-
Channel gradient	-	+	+	-	+ or -	+ or -	-	+

Notes: Q is the stream discharge and QS the bed-load discharge for a river.
+ and - indicate an increase or decrease, respectively, in a variable or characteristic. An empty cell or 0 indicates no change in the variable or characteristic.
Source: Adapted from Petts (1979)

the effects of a dam or other human disturbance is to observe the river channel over time and evaluate changes in channel characteristics. Examples of these types of studies in Texas include studies of the Trinity River's Livingston Dam (Phillips and Mussleman, 2003; Phillips, Slattery, and Mussleman, 2004) and the Sabine River's Toledo Bend Dam (Phillips, 2003).

The potential effects of human-induced disturbances on the geomorphic processes of rivers can be estimated by observing control and response variables. Control variables are large-scale environmental factors that control patterns found in local features. These variables can be measured from maps or other data and include geology, soils, land use, hydrology, planform channel features, and valley characteristics. Response variables are environmental features of the river channel on a more local or site-specific scale. Measurements of these variables are collected in the field at a specific location. Examples of response variables include channel shape, cross-sectional dimensions, substrate, bank shape, floodplain characteristics, vegetation, and channel patterns.

A complete geomorphic assessment is required to adequately understand the effects of human impacts on the physical processes of a river. This assessment can, in turn, be used to better manage the river system. The following aspects of geomorphic analysis are of direct interest to managing river systems:

- Qualitative field methods to identify the stability of the system
- Quantitative studies to trace and survey sediment sources
- Analysis of river channel and planform plus prediction of future changes
- Studies of channel processes (bank erosion, sediment transport, and morphological form processes)
- Preliminary estimates of sediment yields and the impact of man's activities on those yields
- Influence of large floods and climatic change
- Appraisal and design of project impacts and enhancement measures

8.3
GEOMORPHIC ASSESSMENT

A geomorphic assessment of a river channel provides knowledge about the causes and effects of hydrologic or sediment regime changes over time (Rosgen, 2001). The assessment should include historic records, maps, aerial photographs, Digital Orthographic Quarter Quadrangles, streamgage records, and other data sources that illustrate changes the river has undergone. For example, an inspection of historical aerial photographs can indicate changes in meander wavelengths and transverse migration of the channel. To provide a picture of current conditions on the river, the assessment should also include collection of on-site data. By investigating signs left on the landscape, on-site data collection may also provide a picture of past river conditions and human activities near the site. Finally, the assessment should estimate if the channel area is stable or unstable and how long it will remain in this state. In combination with other studies, a geomorphic assessment will lead to a better understanding of human impacts on the river system.

An important outcome of a geomorphic assessment is an understanding of the river system's stability. Rivers are highly dynamic and responsive to changes in their controlling variables. Their sediment transport rates are related to their sediment supplies. Continued removal of sediment from the system will cause the river to find a replacement supply. Geomorphic stability occurs when a river segment adjusts to a change in the sediment or water load without undergoing net erosion or deposition. Conversely, when the response of the river to a change includes significant erosion or deposition, the segment is considered to be unstable. Note that stability is based on net erosion or deposition within a river segment, and the natural process of transverse channel migration does not indicate an unstable river.

Because geomorphic definitions of stability depend on bed material and sediment loading rate, not all changes in river characteristics are signs of system instability or disturbance. For example, a decrease in the sediment transport ability of anabranching rivers (which have multiple, active channels and low migration rates) is considered natural and not a sign of instability (Nanson and Knighton, 1996). In addition, a portion of a river system may be unstable as part of its natural behavior. For example, sand-bedded rivers have a bed that is moving most of the time. In parts of Texas dominated by flash floods, various portions of a river system can be naturally unstable (Baker, 1977; Beard, 1975).

8.3.1

Geomorphic Thresholds

A geomorphic threshold is an energy or mass-transfer level that, when surpassed, causes the river system to seek out a new state of equilibrium. If a geomorphic threshold is not exceeded, minor disturbances in discharge or sediment regime will cause only minor, short-term disturbances to a river's geomorphic behavior. But when a geomorphic threshold is surpassed, even minor disturbances to hydrologic or sediment regimes can cause significant changes in river characteristics. After crossing a threshold, the system will remain unstable until adjustments are made and a new and different stable state is established. During an unstable period, river behavior can change dramatically from predisturbance conditions. For example, water diversion to the Milk River of Montana caused the meander migration rate to increase to 0.85 meters (2.8 feet) per year, and the channel width increased by 5.5 meters or 18 feet (Bradley and Smith, 1984). A channel avulsion (a major change in channel direction, location, or form) is a common response when a geomorphic threshold has been passed and the river system has become unstable.

8.3.2

Assessment of Current Channel Conditions

A geomorphic assessment can be used to identify current or potential problems within a river system. The analysis is based on measurements of physical features of the river system, including planform characteristics, cross-sectional and longitudinal features, and bank and bed materials.

Planform measurements

Planform characteristics of the river should be measured using aerial photographs. A comparison of measurements taken from historical and current aerial photos can be used to analyze changes in the river. These are examples of characteristics that can be measured and compared:

- **Meander belt width**—the distance between lines drawn tangential to the extreme limits of fully developed meanders
- **Sinuosity**—the stream length divided by the valley length
- **Meander wavelength**—the down valley distance between two corresponding points of successive meanders of the same phase

Cross-sectional measurements

Cross-sectional data are collected in the field. This data should include at least the following points from both sides of the channel: floodplain elevation, top and toe of bank, bankfull width and depth, lower limit of vegetation, and water surface. These and other cross-section parameters are recorded from the viewpoint of looking downstream, with the right and left bank defined by this orientation. These are examples of measurements made from cross-sectional data:

- **Base flow width**—the average flow width during base flow conditions. Base flow is the normal level of the flow when the river is not responding to a storm
- **Base flow depth**—the mean depth during base flow conditions
- **Base flow wetted perimeter**—the wetted perimeter as measured during base flow conditions
- **Bank height**—the distance from the top of the bank to the bottom of the bank
- **Bank slope angle**—the angle of the bank made between the lines drawn from the top of the bank to the bottom and one across the channel bed
- **Rooting depth**—the depth from the top of the bank to subsurface level where roots stop their domination. There can be two measurements for this depth, one for grass or understory vegetation and one for tree root masses

Longitudinal feature measurements

Since the elevation of the channel bed varies both laterally and longitudinally, channel slope measurements must be taken carefully. Because the depth of pools varies along the channel, the most accurate way to measure slope is to locate survey points at the top of riffles or ripples and obtain the distance between them. Locations on adjacent riffles are not suitable. Instead, riffles that are separated by at least one additional riffle should be measured. Generally, the crests of at least three riffles are measured. If a relatively straight line is found when the three points are plotted, the slope of the line is considered a good estimate of channel slope. If a straight line is not obtained, additional riffle locations in the upstream or downstream direction are measured.

A longitudinal thalweg profile of a river is an important measurement and is helpful for both hydraulic studies and the identification of bed forms (Madej, 1999). Topographic maps do not produce good quality profiles since they show the water surface and not the bed characteristics. Therefore, channel profiles must be developed from survey points collected from the thalweg at various locations along the length of the river.

There are different methods for evaluating channel bed form depending on the riverbed material. Bed form configurations for sand-bedded streams are defined by the forms created in the bed. These include ripples, dunes, antidunes, and flat beds. These features are formed by different shear stresses acting on the cohesionless bed. Ripples form where shear stress is low and the bed material is fine. Dunes form at intermediate stresses and have a geometry related to the depth of water flow. Antidunes are low amplitude waves that are in phase with the surface water waves. Although these bed forms are common in sand-bedded rivers, the mechanisms that cause their formation in streams are poorly understood.

Bed form configurations in gravel-bedded rivers are defined by across-channel features, such as pools and riffles. At base flow levels, pools generally have a slower velocity with deeper water depth, and riffles have shallower depth and faster velocity. Scour pools are found around logs and other woody debris or large boulders. When one of these objects is moved or repositioned, the configuration of the associated scour pool will also change. Examples of bed form measurements that can be taken for a gravel bed stream include the following:

- **Riffle length**—the distance between the top and bottom of the riffle

- **Riffle gradient**—the change in elevation of the channel bed from the top to the bottom of the riffle divided by the riffle length
- **Inter-pool length**—the longitudinal distance between the deepest points of successive pools, measured along the centerline of the channel
- **Inter-pool gradient**—the change in elevation of the channel bed between deepest points of successive pools divided by the length of the inter-pool distance

Bed and bank material analysis

The materials making up the bed and banks of a stream are an important part of the channel system. They influence the morphological form of the channel, erosion and deposition rates, hydraulics, and other stream functions. Due to the complex interactions of erosion, deposition, and transport, there will be a heterogeneous mix of materials in any river. However, the mean particle size is generally thought to be the controlling influence on physical processes. Boulder-bedded streams contain bed material with diameters greater than 256 millimeters (10.1 inches). Cobble-bedded streams contain bed material with mean diameters between 64 to 256 millimeters (2.5 to 10.1 inches). Gravel-bedded streams have material between 2 to 64 millimeters (0.08 to 2.5 inches) in mean diameter, and sand-bedded streams contain bed material composed of sediment with diameters less than 2 millimeters (0.08 inch). A sieve analysis, as described by Bunte and Abt (2001), is completed in order to determine the size of bed material.

Gravel- and cobble-bedded streams differ from sand- and boulder-bedded streams by more than just bed material size. They also have different stream morphology and occur in different topographic and geological locations. Sand-bedded streams have low gradients and occur in valleys or on broad plains, and gravel- and cobble-bedded streams have steeper gradients and are found in environments with more relief. In Texas, sand-bedded streams occur in the marine deposited sediments of the Coastal Plains or in areas with granite uplifts. Gravel- and cobble-bedded streams occur in and around the Edwards Plateau and similar locations where larger sediment material is produced.

8.4

SEDIMENT BUDGETS

When rocks are weathered, they produce sediment particles that are moved to the stream channel by runoff. Once in the channel, this sediment is transported to the ocean through a long-term cycle of local erosional and depositional actions that reduce the size of the original hill slope-produced particles as they move downstream. Sediment particles can be deposited along the way in alluvial channel-margin deposits, on the floodplain, or in the channel itself. These deposited materials can be re-entrained by the river from the channel, banks, or floodplain.

A sediment budget is an evaluation of sediment particle movement and can be conducted from two viewpoints: what is moving (transport process) or where the sediment is located in the watershed (sediment deposition). Both viewpoints are valuable when analyzing the health of an aquatic system. The transport-process viewpoint focuses on how particles are moved between locations. The method of transport can be as suspended load (fine-grained particles that travel in the water column) or as bed load (coarse-grained material that travels along the channel bed). The sediment-deposition viewpoint is not only interested in what is moving, but also what is temporarily being stored and where.

A sediment budget explains the input, transport, storage, and export of sediment for a particular system. The system could be as large as the Mississippi

River system or as small as an individual landform, such as a hill slope. The sediment budget characterizes the landform being studied by describing the expected changes or evaluating measured impacts on the site (such as rates of erosion or deposition). System activity is explained and the effects of different events (such as flow events) on the landform are described. The final outcome is a prediction of future system responses or a comparison of the responses of similar landforms under different conditions. There are several methods for conducting sediment budget studies related to river systems. Examples include models, analogy, inference, and data from historical records or monitoring. Sediment budget studies also vary based on the processes being investigated, sizes of material of interest, temporal and spatial scales, and available resources and data. For a more complete description of sediment budget studies, see Reid and Dunne (1996). Sediment budget studies for the Texas Instream Flow Program will be tailored to the issues of interest in a particular sub-basin.

An incipient motion study of bed sediment mobility may be included with a sediment budget analysis. Results of such studies could be used to determine flows required to provide preferred sediment characteristics in the channel or minimize bank erosion. Incipient motion studies require an understanding of sediment sizes present plus the transport energy available to move the material. Calculating incipient motion can be a very complex problem and there are several methods from which to choose. For studies in the Texas Instream Flow Program, the choice to conduct an incipient-motion study and the selection of methodology will be decided on a reach-by-reach basis.

8.5
CLASSIFYING A RIVER

Physical processes explain most of the changes in channel structure, aquatic habitat composition, riparian vegetation, and other characteristics of a river as it flows from its headwaters to the ocean. As a result, geomorphic classification of river segments, reaches, and small portions of the channel is an important component of a river study. Results can be used for documenting and analyzing physical river processes and selecting reaches for instream habitat and water quality studies.

There are many types of river classification schemes. Simple schemes can vary from a simple description of the planform to classification based on data from a cross section. More complex classification systems evaluate geomorphic processes at many different scales, such as physiographic province, watershed, valley, channel reach, or morphological unit (see Rosgen, 1996). The National Research Council (2005) suggested that a geomorphic classification scheme for water allocation studies should

- be hierarchical in its structure;
- be physically based;
- include the floodplain;
- relate channel to physiographic and hydrologic setting; and
- contain channel morphology, such as planform, slope, and bed morphology.

River system classification is evolving from simple reach analysis to large geomorphic database analysis with the use of GIS. Geomorphic river classification schemes have been reviewed by Thorne (1997) and Montgomery and Buffington (1998). Kondolf and others (2003) reviewed 21 classification schemes and mentioned several newer schemes that they did not evaluate, including Raven and others (1998) and Brierley and Fryirs (2000). As comprehensive as their review was, there are even more schemes available, including Rowntree and Wadeson (1998) and Parrott and others (1989).

Although there are many river classification schemes to choose from, very few include all of the features recommended by the National Research Council (2005). For example, the first recommended feature for a scheme is a hierarchical nature. To set up that structure, large map units of the classification scheme must interlock with constraints of the small-scale map units. Of the schemes reviewed by Kondolf and others (2003), only two, Bethemont and others (1996) and Frissell and others (1986), have a completely hierarchical nature. Lotspeich (1980) is nearly hierarchical, but does not work on the scale at which fishery data would be collected. Bethemont and others (1996) fail to evaluate physical features of the substrate, sediment load, and morphodynamic adjustments. Frissell and others (1986) meet the first and second criteria of the National Research Council, but their classification system was developed for small, mountain streams.

Brierley and Fryirs (2005) have developed a framework for conducting geomorphic analysis of river systems that has the potential to incorporate all five of the features recommended by the National Research Council. An assessment algorithm, called River StylesTM, based on this framework is currently being used for environmental studies in Australia.

8.5.1

River Styles Framework

The River Styles framework is a scaled hierarchy in both time and space that organizes map units and information about a river system into a structured database. The framework was created in Australia and is used in that nation's river health program. The scheme classifies the parts of a river system by landscape characteristics, river behavior, and potential changes. The latter includes predicting expected future changes, such as those due to human influence or climate-driven effects.

The River Styles methodology works with the natural diversity of river forms and creates classes by an organized, open-ended, and generic procedure. The main spatial map categories are the watershed, landscape unit, river style, geomorphic unit, and hydraulic unit. These categories have different spatial scales and are related hierarchically (Figure 8-1). The geomorphic variables related to a mapping unit are related to the evolutionary time during which changes in geomorphic conditions within that unit occurred.

Landscape characteristics

In an evaluation of landscape characteristics, River Styles divides these characteristics into control and response variables. The control variables include geology, soils, land use, hydrology, and valley characteristics. Response variables are environmental features of the river channel generally collected from field sites.

Geology and climate are high-level controls on the character of a river system. With the aid of a GIS system, these features can be overlaid at a statewide coverage scale. When the two are merged, a new map is created showing the different geologic and climatic areas. By overlaying a map of river systems, the map units that the river touches or crosses can be observed. Each of these areas can be delineated as a different zone of the river.

The United States Soil Conservation Service (1982) provides a map of 20 land resource areas within Texas, which may be further subdivided into smaller Common Resource Areas (NRCS, 2006). These areas are characterized by grouping soils, climate, water resources, and land uses. Though these areas are generally characterized as one continuous unit usually comprising several thousand acres, they can be segmented further. This map can be used to create zones in the river system as the river flows through or along the boundary of each land resource area.

Variability in hydrology and watershed characteristics can also be used to differentiate river segments. As an example, a plot can be made of river mile versus watershed area. When a nonlinear jump occurs on this plot, the river-mile location should be viewed as the boundary of two different units.

Flashiness (a river's tendency to carry a high percentage of its flows in short duration, large-magnitude events that occur infrequently) is an important feature of Texas rivers. The Flash Flood Magnitude Index developed by Beard (1975) varies across the state from 0.14 for the North Sulphur River near Cooper to 0.9 for the West Nueces River near Brackettville. The physical features of rivers with a low index value are predominantly influenced by relatively low-magnitude, frequently occurring floods. The influence of less frequent, large-magnitude floods dominates when the index values are high (Baker, 1977). The Flash Flood Magnitude Index and other statistics related to flow patterns should be calculated to provide a way of comparing Texas rivers.

Changes in valley characteristics, such as valley shape and width and channel location in the valley, can be used to

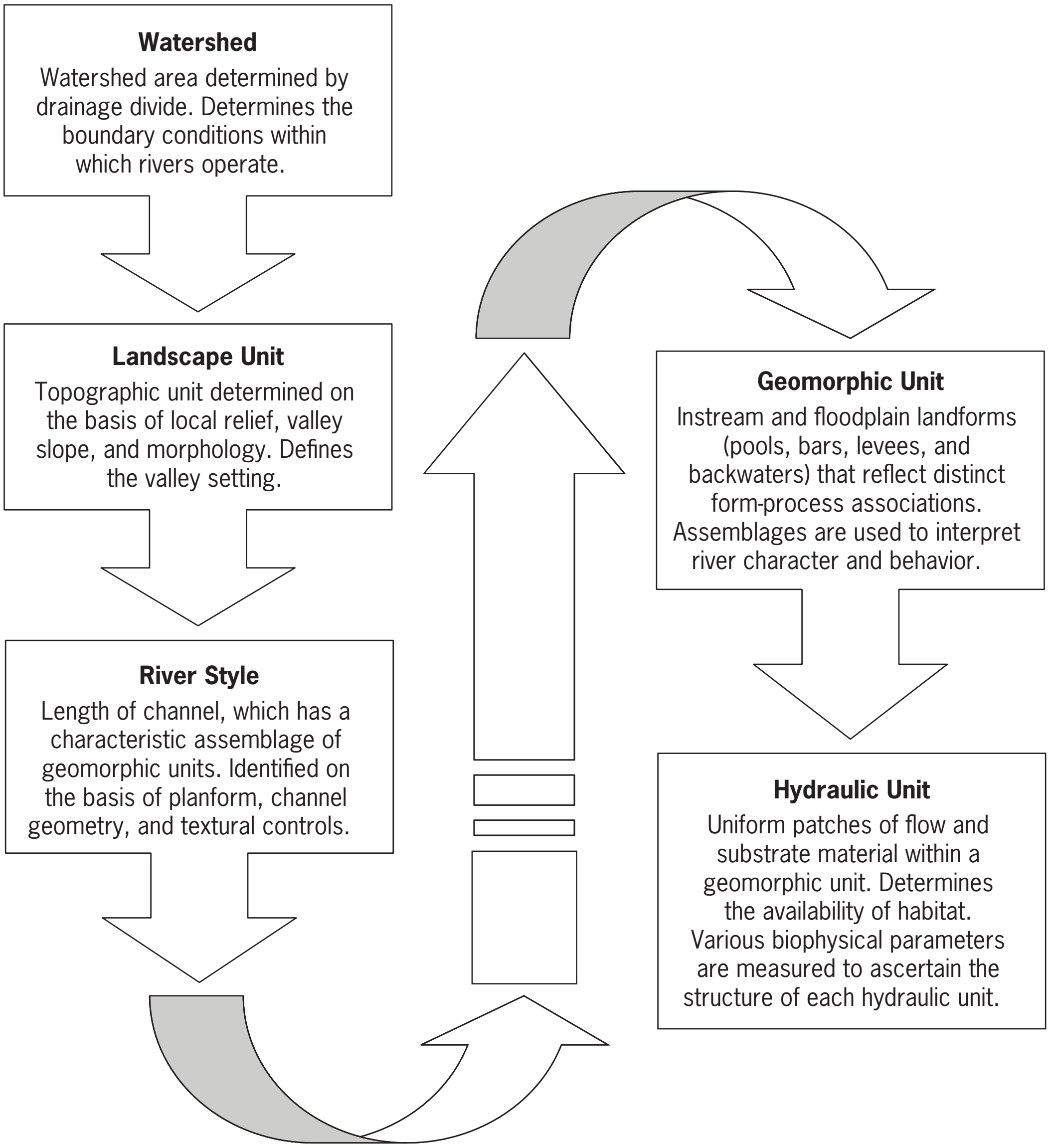


Figure 8-1. Hierarchical relationship of River Styles mapping categories (from Brierley and Fryirs, 2005).

create classification units to further subdivide a river channel system. Channel features, such as channel slope, sinuosity, and channel bed form, are used to further classify channel reaches into large-scale units. The major feature used in this classification is sinuosity as measured from aerial photographs or digital imagery. At a finer resolution, field measurements such as bank and bed composition, vegetation associations, and cross-section characteristics, can also be used to identify geomorphic and hydraulic units.

Just as the channel is connected to the floodplain, the river channel is connected longitudinally to itself. Control conditions for physical processes change along the length of the river, which, in turn, change the characteristics of the channel, floodplain, and valley. A classification based on the River Styles approach seeks to identify the location of these changes in controls and characteristics.

An example of the classification of a river into various river types along its length is shown in Figure 8-2. Although this river system is very simplified, the figure does show how the River Styles method classifies river segments based on significant geomorphic factors.

River behavior

An important part of the River Styles framework is an analysis of the various flow levels that maintain a river's morphometric characteristics and ability to do work. Flow levels are primarily determined by climate (through rainfall), geology (through erosive nature of rocks and soil characteristics), vegetation, and human activities. Flows with a significant impact on river geomorphic behavior are divided into three basic groupings: base flows, high flow pulses, and overbank flows.

Change analysis

Generally, fluvial geomorphology is interested in changes in a river that have occurred since the late Quaternary Period (last 2 million years), including present and possible future changes. A river's response to changes in climate, vegetation, and river base levels over this extended period is related to the system's thresholds. If the changes push a river beyond a threshold value, the river will be actively seeking a new pattern of behavior. If the changes do not exceed a threshold, the river may change for a time but will gradually return to its historical characteristics.

For a major portion of the time period of interest, changes have occurred exclusively due to the forces of nature. These changes in river behavior can be traced to past geologic and climatic history. The earliest civilizations used water courses to fulfill their needs for transportation and water supply. As technology and civilizations have developed, humans have learned to further modify river systems for their own use. Since European settlement of Texas, humans have exerted a strong influence on river behavior. The following direct, human-induced changes have the greatest impact to Texas' rivers:

- **Dams** have been used by humans to capture water for future use and power generation. They change river flow and sediment supply downstream, impacting river processes and creating changes to the river's morphology.
- **Channelization** is a way that humans have engineered rivers to improve flood routing and facilitate shipping and recreational boating. Such "improvements" have been known to completely change the processes of a river and eliminate natural process diversity.
- **Sand and gravel removal** from the riverbed and banks can affect processes by depleting the supply of sediment needed to dissipate the energy of the river.
- **Woody debris removal** from the channel, wetlands, and river corridor

affects flood processes and habitat for wildlife along rivers.

Indirect, human-induced changes to Texas' rivers include these activities:

- **Forest removal** impacts the behavior of small watersheds, causing them to produce more sediment and, in some instances, more runoff. The increased sediment may alter the composition of various parts of the river system, such as gravel bars.
- **Urbanization** affects the soil's ability to absorb water, alters runoff timing, and increases flood magnitude.
- **Mining** in a watershed changes the pattern and timing of water running off the land, exposes chemicals to this runoff, and changes the sediment supplied to the river. The river processes must adjust to these changes.

What the river did in the past helps explain what it will do in the future. If the river had a high meander migration rate while the land use in the watershed was grazing, a change to a more urban area would increase bank erosion. The river may have a constant rate of lateral movement across its floodplain, but this rate may be invisible with short time scale observations. By reviewing aerial photographs and tracing the river's path over long periods of time (50 years), the process and rate of movement becomes clear. The following changes can be identified from historical data:

- Land use pattern
- Channel planform values (sinuosity, width)
- Gradient and channel length
- Bank erosion or protection

Unfortunately, geomorphic data are limited for most river segments in Texas. Without these data, predicting a river's response to water diversions or dams is difficult although some inferences can be made from historical aerial photo-

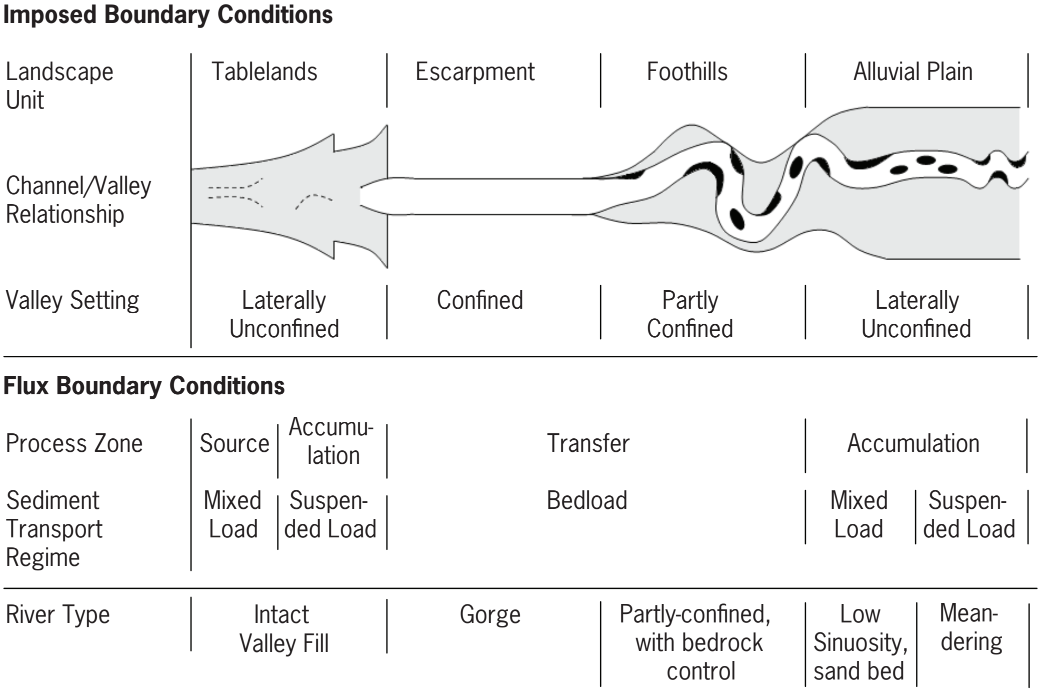


Figure 8-2. Example of longitudinal segmentation of a river system based on River Styles methodology (from Brierley and Fryirs, 2005).

graphs or other sources. The Agencies are exploring the potential of using historical measurement data at U.S. Geological Survey gage locations to make some generalizations about channel aggradation/degradation rates. These types of evaluations could improve the understanding of historic river processes at specific locations.

When historical geomorphic data are not available, change analysis will be limited to observation of trends in the geomorphic processes measured under current conditions. This can be accomplished by sediment budget analysis and initiating a monitoring program that collects geomorphic process data. With this information, the Texas Instream Flow Program can use the following principles to guide interpretation of the system's response:

- Evaluate the river's variability and capacity for change in its valley setting
- Identify the balance between erosional and depositional processes
- Interpret the balance between input variables and resisting forces as time proceeds
- Identify threshold conditions that lead to change
- Estimate how the river system may change with proposed flow regimes

9 *Water Quality*

Water quality issues are linked to other disciplines discussed in this document. From the standpoint of achieving a sound ecological environment, water quality and quantity cannot be separated. Water quality is recognized as an important component of the Texas Instream Flow Program because water chemistry may influence species composition, nutrient cycles, and sediment loadings, among other factors. At the same time, channel morphology, flow, and the physical structure of the riparian zone can directly influence water chemistry. For example, channel-forming processes affect instream habitat that can influence stream reaeration, an important determinant of instream dissolved oxygen and the assimilative capacity for oxygen-demanding constituents. Temperature is similarly affected by channel morphology and the physical structure of the riparian zone through the depth-to-width ratio (or surface area-to-volume ratio) of the channel and by the amount of shading provided by riparian canopy. Dissolved oxygen and temperature are significant water quality components supporting the biological integrity of waters. Hence, water quality both shapes and is shaped by the other forces and agents acting in riverine systems.

This chapter describes the state's existing water quality programs, based on the federal Clean Water Act and the Texas Water Code §26, and demonstrates linkages between water quality and variable flow regimes. The goals and objectives of the state's program include assessing and protecting the physical, chemical, and biological integrity of the state's water bodies. This chapter is focused on water chemistry.

9.1
BACKGROUND

Water quality is an integral component of aquatic ecosystems and must be addressed when evaluating the environmental consequences of modifying flow regimes. Sufficient instream flows are needed to maintain the appropriate physical, chemical, and biological integrity of rivers and streams. The native aquatic community of a stream has adapted to a range of flows and the resulting variations in water quality over time. However, significant changes in both flow and water quality have occurred in Texas rivers during the last 100 years in direct response to human activities. Agricultural, municipal, and industrial water use has reduced flow from some springs. In addition, rivers have been impounded and diverted for the same purposes and for flood control. Each of these activities has noticeable impacts on water quality. For example, impoundments can cause changes in temperature regimes, sediment transport, and nutrient cycling. Wastewater discharge plants are associated with increases in flow, temperature, organic loading, and nutrients in receiving waters. Some of these impacts are unavoidable consequences of human activities (such as loss of sediment transport through reservoirs), and water quality impacts resulting from point source discharges and nonpoint source runoff are addressed through water quality management programs.

The Texas Commission on Environmental Quality has jurisdiction over the state's water quality programs, including adoption of surface water quality standards, enforcement of water quality rules, and issuance of permits, in addition to its water quality planning responsibilities (Texas Water Code §5.013a). The Commission monitors water quality throughout the state, identifies beneficial uses for surface water bodies, adopts water quality standards designed to support the identified uses, and manages water quality through regulating point source discharges and funding remedies for nonpoint source pollution. The Commission prepares the State of Texas Water Quality Inventory and submits the report to the U.S. Environmental Protection Agency biennially in even-numbered years as required by section 305(b) of the Clean Water Act. The most recent submission was prepared in 2004 (TCEQ, 2004a). Additionally, the Commission develops a list of impaired stream segments (segments where one or more of the identified uses is not supported) as required under section 303(d) of the Clean Water Act.

Summaries of applicable programs are presented below; detailed descriptions are located at the Web sites listed with each program.

9.2
WATER QUALITY PROGRAMS IN TEXAS

The Clean Water Act framework, implemented by the Texas Commission on Environmental Quality, has five major components, laid out in the following sequence:

- Establish the uses of the water that will be protected
- Determine the criteria necessary to protect those uses
- Base decisions on meeting those criteria
- Conduct ambient monitoring to ensure criteria are met and uses are maintained
- Require corrective action when it is determined that uses are impaired

9.2.1
Water Quality Standards and Assessment

In order to protect the physical, chemical, and biological integrity of rivers and streams, relevant parameters must be defined and measured, the types and sources of pollution must be identified, and plans to protect or restore water quality must be implemented. Texas uses a varying cycle of activities to manage water quality based on statutorily determined time frames. These steps are included in the cycle:

- Establishing or revising water quality standards
- Determining appropriate aquatic life use designations
- Collecting data at routine, fixed stations or at special project sites
- Assessing water quality and identifying those waters that do not meet established criteria or where one or more uses (such as recreational and public water supply) are not met
- Implementing pollution control measures and monitoring the results

9.2.2
Surface Water Quality Standards

The Texas Surface Water Quality Standards (30 Texas Administrative Code §307.7) fulfill these state and federal requirements:

- Establish uses
- Set criteria to maintain the established uses
- Establish an anti-degradation policy

The rules establish numerical and narrative goals for water quality throughout the state and provide a basis on which Texas Commission on Environmental Quality programs can establish reasonable methods to implement and attain the state's water quality goals.

Water quality standards have been developed for all surface waters in the state. The Commission has developed segment-specific uses and water quality criteria for 225 classified water quality segments representing 14,238 miles (22,909 kilometers) of perennial streams (TCEQ, 2004b). Aquatic life use designations have been determined for an additional 319 unclassified stream segments totaling over 6,000 stream miles or 9,654 kilometers (Table 9-1). Water quality standards have been adopted for all streams that have been identified as priority segments in the Programmatic Work Plan (TIFP, 2002).

Although established aquatic life use designations seem to be a logical place from which to start assessing aspects of a sound ecological environment in Texas rivers and streams, there are limitations to their applicability to the Texas Instream Flow Program. First, the original designations for classified segments were based on dissolved oxygen criteria. Aquatic life use designations were added later under the general assumption that 5.0 milligrams per liter of dissolved oxygen equaled a "high aquatic life use" (6.0=exceptional, 4.0=intermediate). Consequently, designations in classified segments may not be biologically based in some instances. Second, the Index of Biotic Integrity now relied upon for assessing aquatic life uses was developed for small-to-moderately sized streams and has not been tested extensively in larger rivers, such as those selected as priority instream flow segments. The Index (separately determined for both invertebrates and fish) was also designed to be a multistressor indicator of aquatic ecosystem health and not necessarily designed to be strictly flow sensitive. It is not clear if values from the Index of Biotic Integrity would change under a different set of flow conditions. Finally, some elements of a sound ecological environment are not represented by aquatic life use designations. For example, the health of riparian zones may not be fully captured by these designations. The state is committed to protecting designated aquatic life uses and developing instream flow recommendations that will reflect consistency with these designated uses. The Texas Commission on Environmental Quality continues to evaluate the effectiveness of all assessment tools, including the sensitivity of the Index to flow variation and is considering how all stressors, including flow, affect biological integrity. For the purpose of simplicity, it may benefit the Texas Instream Flow Program to heed the recommendation of the National Research Council (2005) and adopt ecological indicators that are linked directly to flow variability.

The Texas Surface Water Quality Standards are available on the Texas Commission on Environmental Quality Web site: www.tceq.state.tx.us/nav/eq/eq_swqs.html

Table 9-1. Attributes of aquatic life use categories.

Aquatic life use	Habitat characteristics	Species assemblage	Sensitive species	Diversity	Species richness	Trophic structure
Exceptional	Outstanding natural variability	Exceptional or unusual	Abundant	Exceptionally high	Exceptionally high	Balanced
High	Highly diverse	Usual association of regionally expected species	Present	High	High	Balanced to slightly imbalanced
Intermediate	Moderately diverse	Some expected species	Very low abundance	Moderate	Moderate	Moderately imbalanced
Limited	Uniform	Most regionally expected species absent	Absent	Low	Low	Severely imbalanced

Source: 30 Texas Administrative Code §307.7(b)(3)(A)(i)

9.2.3

Surface Water Quality Monitoring

The Surface Water Quality Monitoring Program has been evaluating biological, chemical, and physical characteristics of Texas' surface waters since 1967. This program establishes the water quality sampling procedures of the Texas Commission on Environmental Quality and maintains the ambient water quality database collected by the Commission's various partners. A large number of fixed sampling sites are maintained statewide, and special studies and intensive surveys are performed to identify causes and sources of pollutants and quantify point and nonpoint source loads. This program also performs assessments of aquatic life use in unclassified streams and of receiving water in response to discharge permitting action. It also performs use attainability analyses to ensure that water quality standards and criteria are appropriate for a water body. Available guidance allows any qualified practitioner to also perform aquatic life use assessments, receiving water assessments, and use attainability analyses.

The Texas Clean Rivers Program is a collaboration of the Texas Commission on Environmental Quality, 15 water resource agencies (corresponding to the 15 major river basins), and a myriad of other cooperators. The cooperating agencies collect water quality data throughout their respective basins under this program, which allows watershed issues to be addressed at a local level, with coordination at the state level to assure consistency and quality of water quality data.

For details on the Surface Water Quality Monitoring program see: www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wqm/mtr/swqm.html

Details of the Texas Clean Rivers Program are available at this Web site: www.tceq.state.tx.us/compliance/monitoring/crp/index.html

9.2.4

Texas Water Quality Inventory

The state carries out a regular program of monitoring and assessing Texas surface waters to compare conditions to established standards and to determine which water bodies are meeting the standards for their identified uses, and which are not. The Texas Commission on Environmental Quality works in collaboration with state, federal, regional, and local stakeholders to collect and assess this data. The Clean Rivers Program is the primary agent of this monitoring program. Assessment results are published periodically in the Texas Water Quality Inventory and 303(d) List, as required by Sections 305(b) and 303(d) of the federal Clean Water Act.

The Texas Water Quality Inventory and 303(d) List include detailed descriptions of the status of surface waters of the state. These reports document public health concerns, fitness for use by aquatic species and other wildlife, and specific pollutants and their possible sources. The Texas Water Quality Water Inventory and 303(d) List are available on the Texas Commission for Environmental Quality Web site: www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wqm/305_303.html

9.2.5

Texas Pollutant Discharge Elimination System

The State of Texas assumed the authority to administer the National Pollutant Discharge Elimination System program in Texas on September 14, 1998. The program is a federal regulatory program to control discharges of pollutants to surface waters of the United States. The Texas Pollutant Discharge Elimination System program now has federal regulatory authority over discharges of pollutants to Texas surface water, with the exception of discharges associated with oil, gas, and geothermal exploration and development activities, which are regulated by the Texas Railroad Commission.

Under the program, the Texas Commission on Environmental Quality implements the Texas Surface Water Quality Standards when issuing permits for wastewater or other authorized discharges into the surface waters of the state. Water quality models are commonly applied to determine permit limits for dissolved oxygen needed to protect existing aquatic life uses. Since municipal wastewater is the predominant type of wastewater discharge into rivers and streams, much effort has been expended on modeling dissolved oxygen. The type of model used depends on the 1) type of water body, 2) availability of site-specific information, 3) location of the discharge point, and 4) availability of previously developed models. Calibrated models are used when available.

For wastewater discharge permits, one critical dilution flow is defined as the instream flow necessary to meet established human health and aquatic life criteria. Acute and chronic aquatic life criteria have been adopted that account for both frequency and duration of exposure to stressors. The critical dilutions are the 7Q2 flows for chronic aquatic life criteria, and one quarter of the 7Q2 flows for acute aquatic life criteria. A functional aquatic environment with its requisite flows provides assimilative capacity, and the Commission's water right permitting program recognizes the important linkage between water quality and quantity. As a result, the Commission coordinates its recommendations for special conditions for water right permits with the appropriate water quality programs. Although the critical dilution flow is functionally used for modeling parameters such as dissolved oxygen during low flow, high temperature periods (worst-case scenario), those flows are not necessarily suitable for supporting a sound ecological environment on a long-term basis.

For details on the Texas Pollutant Discharge Elimination System procedures see: www.tceq.state.tx.us/permitting/water_quality/wq_assessment/standards/WQ_standards_implementing.html

9.2.6
Total Maximum Daily Loads

The Total Maximum Daily Load program works to improve and restore water quality in impaired or threatened water bodies in Texas. To restore quality, it is first necessary to determine the sources and causes of the pollution. The goal of a Total Maximum Daily Load project is to

- determine the maximum amount of pollutant that a water body can receive and still both attain and maintain its water quality standards; and
- allocate this allowable amount (load) to point and nonpoint sources in the watershed.

Total maximum daily loads must be submitted to the Environmental Protection Agency for review and approval. A total maximum daily load is normally prepared for each pollutant in every impaired water body. Based on the environmental target, the state develops an implementation plan to mitigate human-caused sources of pollution within the watershed and restore full use to the water body. An implementation plan outlines the steps necessary to reduce pollutant loads through regulatory and voluntary activities. The program is authorized by and created to fulfill the requirements of Section 303(d) of the Clean Water Act and its implementing regulations. Detailed information on the program is available on the Texas Commission on Environmental Quality Web site: www.tceq.state.tx.us/implementation/water/tmdl/index.html

9.3

WATER QUALITY FOR INSTREAM FLOW STUDIES

Texas has invested considerable resources in developing water quality models, especially in the Total Maximum Daily Load and Texas Pollutant Discharge Elimination System programs. The application of water quality modeling approaches used for total maximum daily load development and permitting decisions to instream flow studies will provide consistency among programs; this is particularly important for regulatory programs like the Pollutant Discharge Elimination System and water rights permitting and for developing and protecting water quality standards. To ensure that results and recommendations related to water quality are integrated with the state's water quality standards and regulatory framework, water quality studies identified in the Texas Instream Flow Program's study design process will be closely coordinated with the Commission's existing water quality programs.

The selection of a specific water quality modeling approach depends on a number of factors, including but not limited to 1) the temporal and spatial scale needed, 2) the geomorphic and hydraulic characteristics of the water body, and 3) the constituents of concern. Since the instream flow program will emphasize rivers and streams, the modeling approaches that have been applied to lotic segments are particularly appropriate.

For example, temperature regimes play an important role in many Texas rivers and streams. Spring-fed streams with stable hydrographs and temperature regimes (such as the San Marcos and Devils rivers) support unique ecosystems with relatively stenothermal faunal and floral components. Water temperature at the spring source is usually constant (or nearly so) year round, and the volume of flow influences the downstream extent of thermally suitable habitat during all seasons. Several of the species are endemic and are listed as federally endangered. In response to these factors, Saunders and others (2001) selected SNTEMP, a steady-state model that predicts mean and maximum daily water temperature in relation to stream distance (Bartholow, 1989), to evaluate the effects of flow on temperature regimes in the San Marcos River. In a similar manner, the choice of water quality modeling approach for the Texas Instream Flow studies will be made based on the circumstances of each study.

The spatial resolution needed for a model depends largely on the type of water body to be evaluated and its hydraulic characteristics. Water quality attributes of rivers and streams change longitudinally as various constituents are input, assimilated, deposited into the sediments, and re-suspended. Streams usually exhibit vertical and lateral homogeneity because of turbulent transport of chemical constituents. Consequently, a longitudinally segmented, one-dimensional water quality model such as QUAL-TX (described by Ward and Benaman, 1999a), a modification of the U.S. Environmental Protection Agency's QUAL-2E, is considered sufficient for modeling dissolved oxygen and temperature in most stream segments. In the absence of site-specific information, QUAL-TX is the model most commonly applied by the state's water quality program. It includes regionally specific hydraulic relations and a "Texas" equation for stream reaeration developed from site-specific field measurements (Ward and Benaman, 1999b). QUAL-TX also excludes a number of subroutines found in QUAL2E that are of limited utility in Texas, such as ice cover. QUAL-TX is suitable for the purpose of modeling the effects of pollutant loadings on dissolved oxygen.

Rivers and streams exhibit seasonally predictable variations in water quality throughout most of Texas. The warmest temperatures (late summer) typically coincide with the lowest flows of the year, causing water quality conditions that may be stressful to aquatic organisms. Since this appears to be a well-defined period critical to maintaining the health of aquatic communities, the Texas Commission on Environmental Quality has focused water quality modeling, especially for dissolved oxygen, on these critical conditions, using the QUAL-TX model. Because QUAL-TX is a steady-state model, it is not as useful for predicting water quality under a variety of other flow conditions (such as high flow pulses and overbank flows). An ideal model would simulate water chemistry and temperature under a full range of flow conditions to assess the effects of alternative management strategies; account for sediment and nonpoint source loadings from watershed activities; incorporate point-source discharges, instream chemical transformation processes and sediment transport; and capture local-scale variation in flow and water quality conditions based on instream habitats (NRC, 2005). Unfortunately, no single model is currently available to accomplish all these feats. Part of the strategy for integrating instream flow study elements will require new ways of thinking about how to model water quality parameters in conjunction with the four flow components. The Texas Commission on Environmental Quality will address alternate water quality models or emerging technologies such as hydrologic information systems (NRC, 2005) as budget and time permits.

All of these program components must be re-evaluated on a cycle varying from two to five years. Water quality studies identified as instream flow study tasks will be closely coordinated with the Commission's existing water quality programs. This will minimize redundancy of efforts and ensure consistency among programs.

10 *Integration*

As described in Chapter 4, stakeholder involvement will be sought in each step of the instream flow study process, including integration of data to generate flow recommendations. When field studies are completed, the Agencies will conduct workshops to present and explain the results to the sub-basin workgroups. During those workshops, the Agencies will garner stakeholder input on the methods used to integrate data and generate the instream flow recommendations.

As discussed in Chapter 6, descriptions of flow recommendations will include four components of the hydrologic regime: subsistence flows, base flows, high flow pulses, and overbank flows (Table 10-1). As the studies for the Texas Instream Flow Program evolve, definitions and objectives for these flow components may need to be modified, and additional flow components may be required to support a sound ecological environment for a specific river sub-basin. Results of technical studies in hydrology and hydraulics, biology, geomorphology, and water quality will be integrated to make recommendations for these flow components. Important connectivity linkages within the river ecosystem will also be considered, as well as interannual and intra-annual hydrologic variation.

10.1
SUBSISTENCE FLOWS

The primary objective of subsistence flow recommendations will be to maintain water quality criteria. Secondary objectives for a specific sub-basin may include providing life cycle cues based on naturally occurring periods of low flow or providing habitat that ensures a population is able to recolonize the river system once normal, base flow rates return.

Developing recommendations for subsistence flows requires integrating technical studies from various disciplines (Figure 10-1). Biological studies will identify key considerations related to these reduced flow rates. Examples include identifying location and characteristics of refuge habitats for species during low flow events and describing the effect of

Table 10-1. Definitions and objectives for instream flow components.

Subsistence flows
Definition: Infrequent, seasonal periods of low flow
Objectives: Maintain water quality criteria

Base flows
Definition: Normal flow conditions between storm events
Objectives: Ensure adequate habitat conditions, including variability, to support the natural biological community

High flow pulses
Definition: Short-duration, in-channel, high flow events following storm events
Objectives: Maintain important physical habitat features
Provide longitudinal connectivity along the river channel

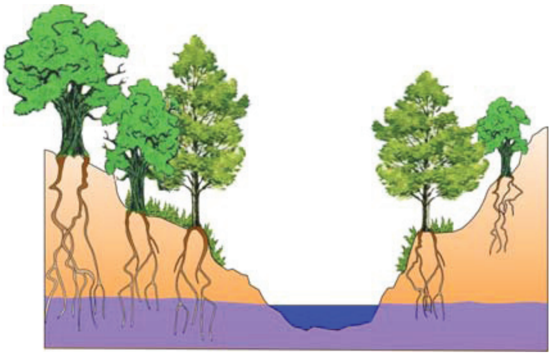
Overbank flows
Definition: Infrequent, high flow events that exceed the normal channel
Objectives: Maintain riparian areas
Provide lateral connectivity between the river channel and active floodplain

Subsistence Flows

Spatial scale:
River Reach

Temporal scale:
Hourly Flow, Varies from Month to Month

Primary discipline:
🟦 Hydrology/Hydraulics
🟩 Biology
🟧 Geomorphology
🟥 Water Quality



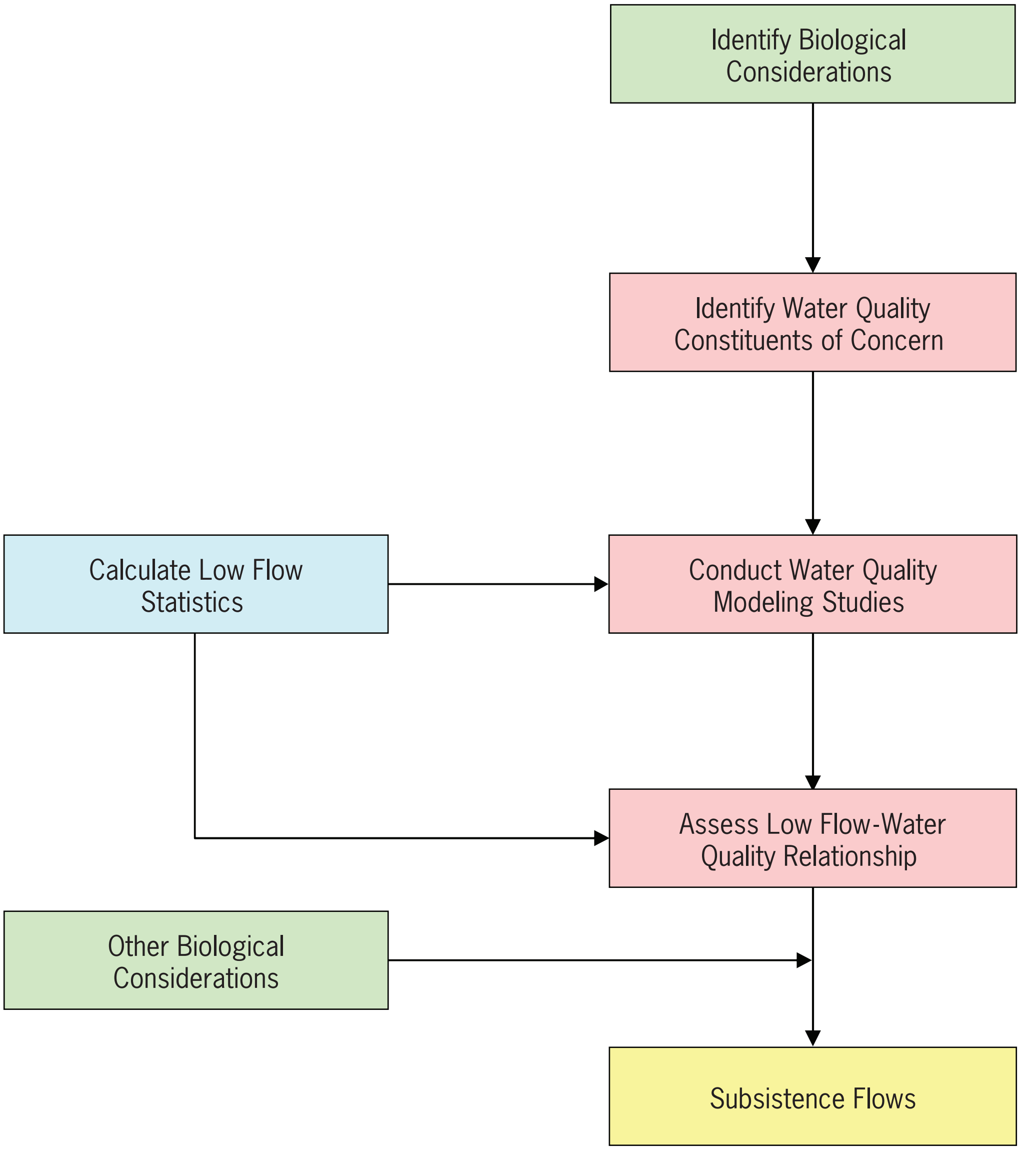


Figure 10-1. Development of subsistence flow recommendations from results of multidisciplinary activities.

such events on important species or communities. Based on these considerations, water quality constituents of concern will be identified. Examples include stream temperatures and dissolved oxygen concentrations determined to be detrimental for certain species or chemical constituents whose elevated concentrations are identified as concerns by the Agencies and stakeholders. Appropriate water quality modeling studies will be conducted to assist in determining the relationship between low flows and constituents of concern (see Chapter 9). Example studies include application of QUAL-TX or other computer models. Hydrologic studies will assist by calculating low flow statistics characterizing the natural occurrence and severity of low flow events. Statistics of interest include 7Q2 flow, which is used in regulating water quality standards. Subsistence flow recommendations will be drafted in order to reduce unnatural variation in constituents of concern. After checking the impact on other biological considerations, subsistence flow recommendations will be finalized.

10.2

BASE FLOWS

The primary objective of base flow recommendations will be to ensure adequate habitat conditions, including variability, to support the natural biological community of the specific river sub-basin. These habitat conditions are expected to vary from day to day, season to season, and year to year. This variability is essential in order to balance the distinct habitat requirements of various species, guilds, and assemblages.

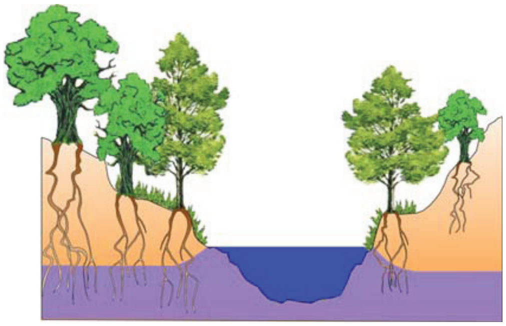
Developing recommendations for base flows requires integrating technical studies from various disciplines (Figure 10-2). Biological studies will identify key species and habitat issues related to a specific sub-basin. Geomorphic studies will assess channel bed forms and banks, and hydrologic studies will calculate base flow statistics for the sub-basin. Results of these studies will assist biologists in determining sites and flow conditions for biological data collection. Based on these data collection efforts, biologists will determine habitat criteria for target species or guilds. For each intensive habitat study site, a hydraulic model will be used to evaluate hydraulic characteristics over the range of flows of interest. A GIS-based physical habitat model will be used to assess habitat versus flow relationships, including diversity (described in Section 10.2.1). Base flow recommendations will include ranges of flow appropriate for wet, average, and dry hydrologic conditions as defined by studies of the specific river sub-basin. Recommendations will be finalized after assessing biological considerations related to water quality for these flow ranges.

10.2.1

Physical Habitat Model

A GIS-based physical habitat model is used to predict habitat conditions within a habitat study site for a range of simulated flow conditions. Hydraulic models provide the simulated flow conditions; geographic coverages provide information about substrate and cover. From these data, GIS forms a spatially explicit habitat model that can be used to query spatial information. For each simulated flow, the spatial availability of suitable habitat can then be queried using habitat suitability criteria for habitat guilds and target species. For each guild and target species, a microhabitat-discharge relationship is developed to provide information on how microhabitat suitability changes with respect to streamflow. Similarly, using mesohabitat criteria, the habitat model can be queried to develop spatial maps of mesohabitat and mesohabitat-discharge relationships at each simulated flow. Spatial maps of mesohabitat can be further analyzed using landscape analysis software (such as Fragstats) to describe habitat heterogeneity in terms of diversity, patch size, location of edg-

Base Flows



Spatial scale:
River Reach

Temporal scale:
Daily Flow Range, Varies from Month to Month

Primary discipline:

🟦 Hydrology/Hydraulics
🟩 Biology
🟧 Geomorphology
🟥 Water Quality

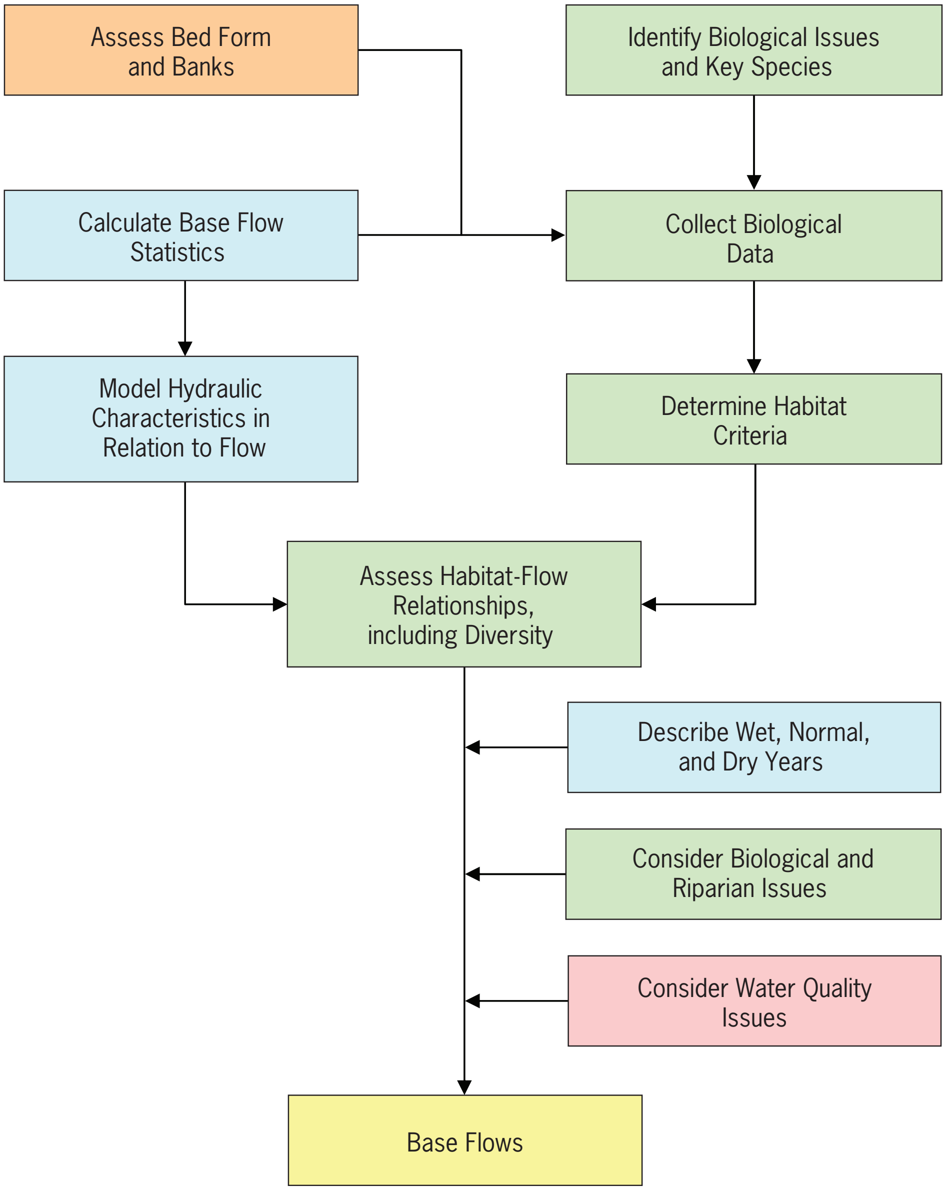


Figure 10-2. Development of base flow recommendations from results of multidisciplinary activities.

es and transition zones (ecotones), and other landscape metrics.

Habitat time series will be produced using hydrologic time series and microhabitat-discharge relationships and, separately, relationships between habitat heterogeneity and discharge. By comparing hydrologic time series derived from naturalized and alternative flow regimes, implications of changes in flow regimes can be assessed. For example, the percent reduction in habitat area between flow regimes can be calculated to help identify time periods of greater or lesser impact. Coupled with data on critical time periods of life history events (such as spring spawning of fishes), habitat time series can help identify when particular inter- or intra-annual flow levels are necessary.

Habitat duration curves can be derived from time series as well. From these curves, mean values and exceedance probabilities of different habitat conditions (such as 85th percentile habitat values and minimum and maximum diversity) can be calculated. Coupled with habitat thresholds (Capra and others, 1995; Bovee and others, 1998; Saunders and others, 2001), duration curves can be used to assess how often and for how long periods of flow result in habitat conditions below, above, or at a threshold. Overall, many combinations of spatial and temporal analyses are possible and can be used to identify base flow conditions that minimize impacts on or maximize value of microhabitat conditions, key habitats, and habitat heterogeneity.

10.3
HIGH FLOW PULSES

The primary objectives of high flow pulse recommendations will be to maintain important physical habitat features and longitudinal connectivity along the river channel. Many physical features of a river or stream that provide important habitat during base flow conditions cannot be maintained without suitable high flow pulses. High flow pulses also provide longitudinal connectivity along the river corridor for many species. Secondary objectives for high flow pulses may include improving recruitment for specific species or other basin-specific objectives.

Developing recommendations for high flow pulses requires integrating technical studies from several disciplines (Figure 10-3). Geomorphic studies will assess active channel processes that shape the physical features of the riverine system. Those studies will also develop sediment budgets to describe the transport and storage of various sizes of sediment within the river system. Finally, geomorphic studies will assess the channel-adjusting flow behavior of the river within the sub-basin. Biological studies will identify biological considerations related to high flow pulses, including water quality. If necessary, additional studies to consider water quality issues will be completed. Hydrologic studies will calculate high flow statistics to describe the historical and current magnitude, frequency, timing, and shape of high flow pulses. Final recommendations for high flow pulses will balance current sediment supplies and flow regimes to achieve desired results.

10.4
OVERBANK FLOWS

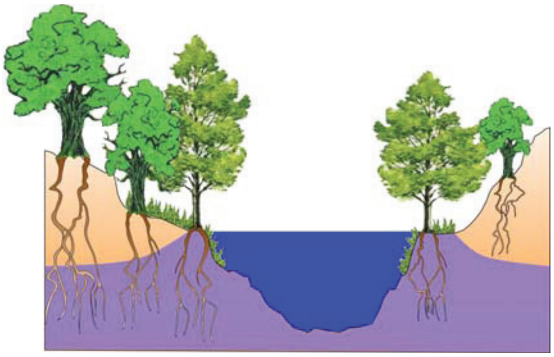
The primary objectives of overbank flow recommendations will be to maintain riparian areas and provide lateral connectivity between the river channel and active floodplain. Requirements for maintaining riparian areas will be specific to each river sub-basin but may include transporting sediments and nutrients to riparian areas, recharging floodplain aquifers, and providing suitable conditions for seedlings. Requirements for lateral connectivity will also vary according to basin-specific factors, such as the presence of fish or other biota using floodplain habitat during and after flood events. Second-

High Flow Pulses

Spatial scale:
River Segment

Temporal scale:
Multiple High Flow, Pulses Throughout the Year

Primary discipline:
🟦 Hydrology/Hydraulics
🟩 Biology
🟧 Geomorphology
🟥 Water Quality



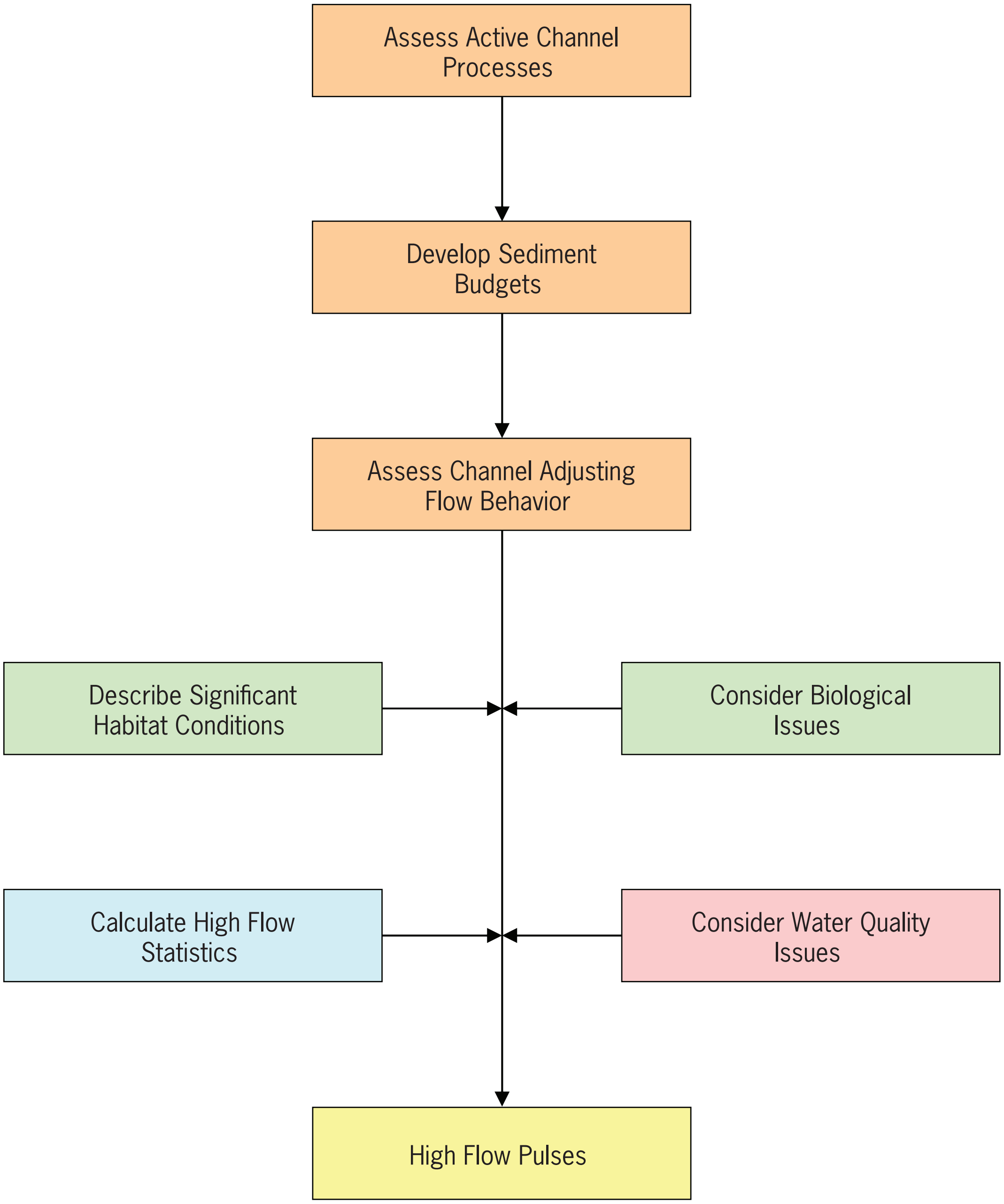


Figure 10-3. Development of high flow pulse recommendations from results of multidisciplinary activities.

ary objectives for overbank flows may include moving organic debris to the main channel, providing life cycle cues for various species, and maintaining the balance of species in aquatic and riparian communities.

Developing recommendations for overbank flows requires integrating technical studies from various disciplines (Figure 10-4). Geomorphic studies will assess the active floodplain and channel processes. Hydrologic studies will calculate flood frequency statistics, and hydraulic studies will model the extent of inundation associated with flood events. This information will assist in assessing overbank flow behavior, which will be used to develop recommendations for overbank flows. Initial recommendations will be based on providing flows that inundate the active floodplain and provide sufficient flow and stream power for active floodplain processes. After conducting riparian studies, biologists will determine riparian requirements, such as timing and duration of events, which will be used to modify initial recommendations. Studies will identify biological considerations related to overbank flows, as well as water quality considerations. Examples of biological considerations include flood recession rates to minimize stranding of fish in floodplain areas or the amount of habitat available for biota using floodplains. Final recommendations for overbank flows will address all of these considerations.

10.5
OTHER CONSIDERATIONS

Before final instream flow recommendations are made, the Texas Instream Flow Program will consider other factors for a specific river sub-basin that may not have been addressed by technical studies. For example, these factors include compatibility with other state and federal programs related to surface water resources (such as freshwater inflow requirements to bays and estuaries). The Agencies will ensure compatibility with the statutory responsibilities of river authorities and other regional water resource management agencies by including these entities as stakeholders during the completion of sub-basin studies.

Because the Agencies are directly involved in many of these programs, they are in a unique position to ensure that the Texas Instream Flow Program is compatible with other state and federal water resource programs. State freshwater inflow requirements for bays and estuaries are developed based on data collection and analytical studies jointly completed by the Texas Water Development Board and Texas Parks and Wildlife Department. The Texas Commission on Environmental Quality administers the state Total Maximum Daily Load Program required by the federal Clean Water Act. In the Texas Clean Rivers Program, the Commission collaborates with 14 partner agencies to conduct water quality monitoring, assessment, and public outreach activities. The Texas Water Development Board facilitates water supply planning efforts mandated by Texas state law. The Texas Parks and Wildlife Department regulates fish and wildlife resources. Through these and other programs and activities, the Agencies have working relationships with many state and federal agencies, allowing communication and cooperation regarding program compatibility.

10.6
STUDY REPORT

The Agencies will prepare a final study report for each specific river sub-basin. The report will include instream flow recommendations for flow components such as subsistence flows, base flows, high flow pulses, and overbank flows. It will also describe the significance of each flow component for the specific river sub-basin and fully document study methods and analysis techniques.

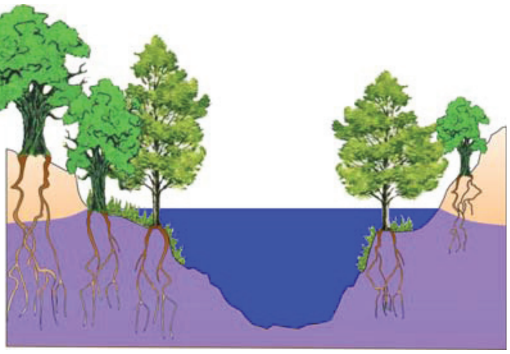
Each study report will include

Overbank Flows

Spatial scale:
River Segment

Temporal scale:
Extreme Flow Events, Occur Less Than Once per Year

Primary discipline:
🟦 Hydrology/Hydraulics
🟩 Biology
🟧 Geomorphology
🟥 Water Quality



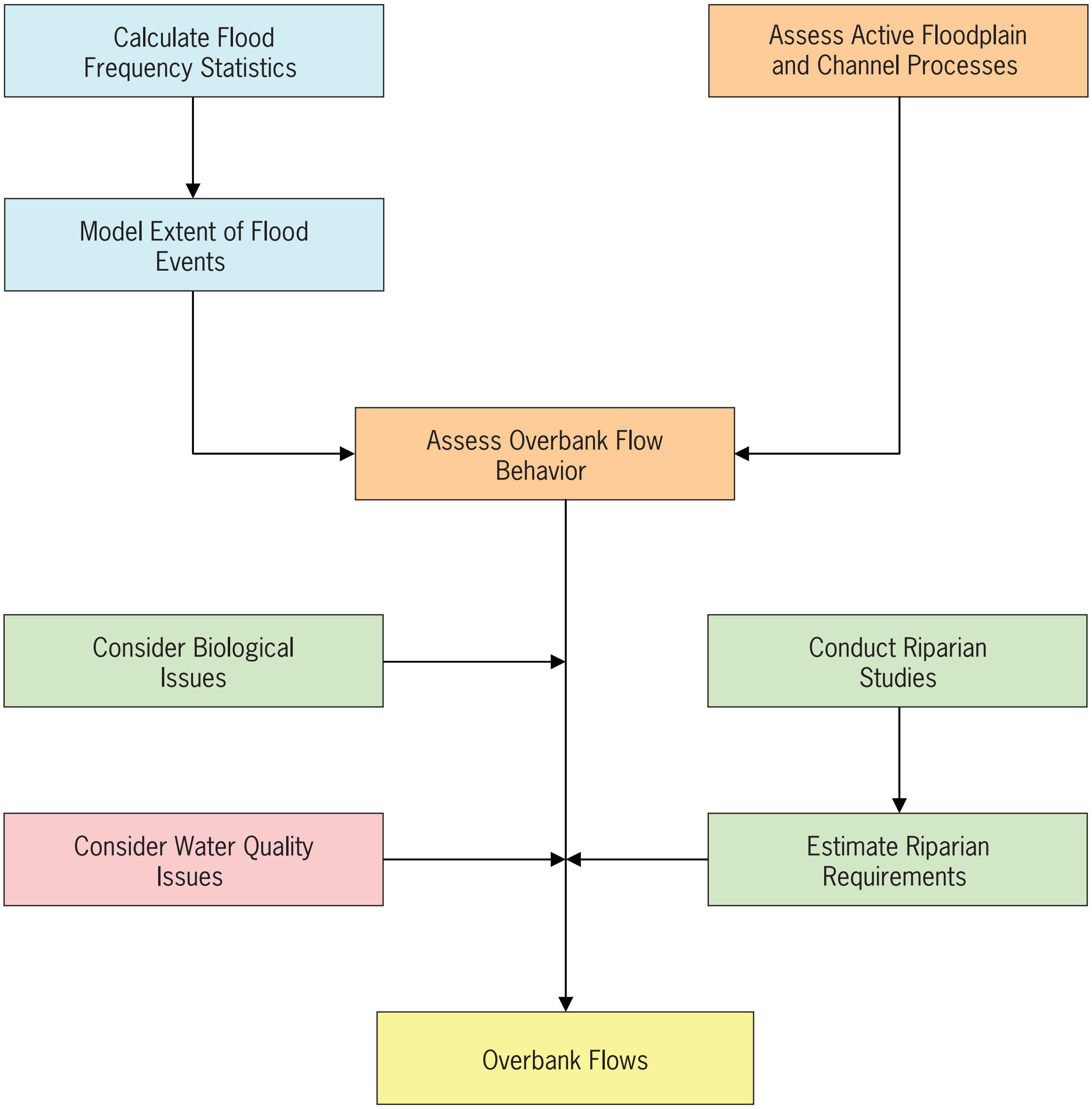


Figure 10-4. Development of overbank flow recommendations from results of multidisciplinary activities.

descriptions of the scientific realities related to instream flow recommendations for the specific river sub-basin (see Section 2.2.2). In addition, the report will identify factors, including flow alteration, that are inhibiting the achievement of a sound ecological environment within the specific river sub-basin. The report will also document uncertainty in study results and conclusions, as well as opportunities to adapt, refine, and improve flow recommendations through additional data collection, monitoring, or analysis. Alternative flow regimes and their consequences will be described.

The draft study report will be written after meeting with the sub-basin workgroups and obtaining their input related to integrating data and generating instream flow recommendations. The draft study report will then be submitted to scientific peer review, as described in Chapter 4. After completing any necessary changes identified by peer review, the report will be presented to stakeholders for further comment before being finalized. The final report will include feedback received from stakeholders and peers, along with responses from the Agencies.

11 *Next Steps: Implementation, Monitoring, and Adaptive Management*

The product of the Texas Instream Flow Program, as envisioned by Senate Bill 2 of the 77th Texas Legislature, is a series of instream flow recommendations that will achieve a sound ecological environment in rivers and streams. After study reports are completed, an additional process will be necessary to translate recommendations into action.

Senate Bill 3, passed by the 80th Texas Legislature in 2007, creates a process to generate regulatory environmental flow standards based on "the best available science." That legislation ensures that the development of management strategies to meet instream flow recommendations will be ongoing and adaptive and will consider and address local issues. Management strategies will outline steps or policies requiring adoption by state agencies, stakeholders, and possibly the legislature to implement new flow regimes. The strategies will also include recommendations related to monitoring and adaptively managing the aquatic environment through periodic review and refinement of flow recommendations. Senate Bill 3 creates opportunities to use the Texas Instream Flow Program studies in developing the regulatory framework necessary to support a sound ecological environment.

The Senate Bill 3 process has already begun, with instream flow recommendations for certain basins due prior to the completion of the detailed Texas Instream Flow Program studies for those areas. Technical experts participating in the Senate Bill 3 process will make recommendations based on the best science available. In the event the Texas Instream Flow Program completes a detailed study after the Senate Bill 3 process has made initial flow recommendations for an area, the results of the detailed study may be considered as part of the process of reviewing and refining flow recommendations. Senate Bill 3 mandates that this review occur at least once every 10 years.

11.1
IMPLEMENTATION ISSUES

The implementation of flow recommendations developed by the instream flow program is addressed by Senate Bill 3. The legislation initiates a process for developing management strategies to meet flow recommendations generated from the best available science, including Texas Instream Flow Program studies. The Senate Bill 3 process will also address environmental flows for specific bay and basin systems. These flows include both freshwater inflow requirements to bays and estuaries and instream flow requirements within the basin. Results of the instream flow program and other studies will provide a scientific basis for selecting environmental flows in portions of basin and bay systems.

For each river sub-basin studied by the Texas Instream Flow Program, a full complement of modeling and analyses will be used to derive instream flow recommendations for a complete range of flow patterns that would collectively achieve a sound ecological environment. The program seeks to identify a range of flow components, from subsistence to overbank flows, (a flow regime) to ensure that the variability in physical, biological, and chemical processes is maintained through time. Additionally, flow regimes will be tailored to specific hydrologic conditions. For example, annual flow regimes (with monthly or seasonal targets) can be developed for dry, average, and wet hydrologic conditions. As a result, specific flow or management objectives and corresponding recommendations can be derived for each of these conditions. For example, during dry conditions objectives might include, but would not be limited to, water quality conditions needed for key or indicator species to survive. During wet conditions, objectives may include, but will not be limited to, riparian and channel maintenance. Desired habitat conditions or indicators could be developed for each hydrologic condition.

Implementing flow recommendations will be a pivotal step in the instream flow program, and a necessary component of implementation will be striking a balance between human needs and ecosystem requirements for fresh water. This balance may be more easily struck in regions of the state where freshwater resources are plentiful due to climatic or other conditions. Implementation challenges will arise from the disparate legal treatment of surface and groundwaters that are hydrologically connected and from ever-changing land uses that directly affect watershed dynamics. Different sets of issues will be confronted in systems with rivers impounded by large storage reservoirs, river basins with unallocated water, and fully appropriated river basins.

A legitimate concern is that by the time the instream flow recommendations are available for a particular sub-basin, human water demands may outpace supplies. Senate Bill 3 addresses this concern by mandating that basin and bay expert science teams recommend environmental flow regimes based on the best science available. This will provide a measure of protection to areas where studies have not yet been completed. Once flow recommendations have been made, other provisions of Senate Bill 3 ensure they will be reviewed, monitored, and refined in the future when the Texas Instream Flow Program or other scientific studies are completed. As part of their duties under Senate Bill 3, basin and bay area stakeholder committees will be required to develop strategies to meet instream flow recommendations.

Results of the Texas Instream Flow Program will be in a form that can be readily integrated into the Senate Bill 3 process. Study results will be documented in a report (see Chapter 10) that will provide a basis for implementation. Information in the report will include a revised conceptual model of the aquatic ecosystem in a specific sub-basin. The report will detail the ecological significance of flow recommendations, discuss the uncertainties associated with analyses, anticipate needs for adaptive management, and describe some of the non-flow-related factors affecting ecosystem health. The report may also describe options for adjusting river operations to meet study goals or topics for additional study should resources become available in the future. To form management strategies for implementing instream flow recommendations as part of environmental flows for basin and bay systems, stakeholder committees established by Senate Bill 3 may adapt study results from the Instream Flow Program.

The Texas Instream Flow Program has identified six priority river basins in which to initiate studies and implement recommendations (TIFP, 2002). These priority basins represent a small subset of the total number of rivers and streams in the state. Ultimately, the program will need to be expanded to encompass these other rivers and streams. Expansion should be based on a priority-setting system and may involve additional studies.

In addition, the Agencies anticipate that classification tools will be developed to aid in applying instream flow standards to the state's myriad rivers and streams. It would be a nearly impossible task to individually study all of the state's 191,000 river miles (307,385 kilometers). By determining hydrologically, ecologically, and geomorphologically similar aquatic ecosystem units, the Agencies could establish and apply streamlined methods for developing instream flow recommendations. This type of approach is being successfully used in New Jersey and is under development in other states (Henriksen and others, 2006).

11.2
MONITORING

A monitoring program is required in order to evaluate the effectiveness of implemented flow regimes in meeting resource management objectives. Senate Bill 3 tasks basin and bay stakeholder committees with developing work plans that include monitoring. Results of the Texas Instream Flow Program will assist in developing these monitoring plans for the instream portion of specific subbasins. Monitoring will be considered during the design phase of the program's studies when goals, objectives, and indicators are developed for a subbasin. A successful monitoring program will need clear goals and objectives that provide the basis for scientific investigation, appropriate allocation of resources for data collection and interpretation, quality assurance procedures and peer review, flexibility that allows modifications when warranted by changes in conditions or new information, and access to "user-friendly" monitoring information by interested parties.

Networks for monitoring aspects of the state's rivers and streams already exist (such as the U.S. Geological Survey streamflow gages, Texas Clean Rivers Program, and university studies), and these data sources should be integrated into an instream flow monitoring program. Additional monitoring should be designed to complement existing sources and ensure adequate coverage of the four study components (hydrology, biology, geomorphology, and water quality) consistent with implementation goals.

A comprehensive monitoring program should be based on a suite of ecological indicators adapted to

- describe the biological, chemical, physical, and hydrologic characteristics of the reach prior to the initiation of field studies (establish current conditions);
- address the goals and objectives of the study recommendations;
- address changing water management strategies with sufficient flexibility;
- evaluate the long-term effectiveness of permit conditions or operational plans in meeting the stated objectives; and
- provide a sound technical basis for recommending adjustments to operational plans in the event that objectives are not being achieved.

11.3
ADAPTIVE MANAGEMENT

The final step of the instream flow program is targeted at addressing the uncertainty of management outcomes that arise from the complexity of the natural environment. Adaptive management, that is an experimental or "scientific" approach to managing resources, is a concept that is gaining acceptance by the resource conservation and management community (Salafsky and others, 2001). The basic premise of adaptive management is the realization that even the best-informed decisions sometimes fail to achieve a desired end result because of faulty assumptions or changing circumstances, including new concerns, altered watershed land use or cover, or new policy initiatives. Through systematic testing of management assumptions, recommended strategies can be modified to ensure that goals are achieved. The Texas Instream Flow Program will not be successful if instream flow recommendations are implemented but there is no further analysis of whether goals were attained. It is highly likely that much will be learned in the early years of implementation of instream flow recommendations. It should be expected that various aspects of the program, from instream flow study design to integration of multidisciplinary information to the establishment of monitoring programs, will be modified as new techniques and ideas are formulated and experience and knowledge are gained.

12 *Conclusion*

The goal of the Texas Instream Flow Program is to determine flow conditions necessary for supporting a sound ecological environment within the rivers and streams of Texas. This document describes the general process and scientific studies the Agencies will use to make those determinations. Studies will be multidisciplinary in nature, including the disciplines of hydrology and hydraulics, biology, geomorphology, and water quality, and will address linkages between and within disciplines. Results will be integrated to develop a flow regime composed of several flow components (such as subsistence and base flows, high flow pulses, and overbank flow components) for a variety of hydrologic conditions (wet, average, and dry). The Agencies expect to gain significant understanding of large riverine ecosystems during these studies. This understanding will be used to refine methods and procedures for future studies and will be documented in future revisions of this or other documents.

In collaboration with local stakeholders, study-specific goals, objectives, and indicators consistent with a sound ecological environment will be determined for each sub-basin and will play an important role in selecting technical methods to determine instream flow requirements. The manner in which the Agencies solicit and incorporate stakeholder input and local knowledge is being developed and will be refined during initial studies. This process is described in general terms in Chapters 4 and 5. As greater understanding is developed in this area, the description of this process will be further clarified in future revisions of this or other documents.

This document is intended to describe the general framework of the process. It does not provide an exhaustive list of the conditions that might be encountered during instream flow studies in Texas. It does, however, describe the organizational process the Agencies will follow to assess available data, set goals, conduct studies, integrate results, develop and implement recommendations, monitor river conditions, and adapt recommendations as necessary. It also describes the general technical capabilities that the Agencies can provide in support of instream flow studies.

The Texas Instream Flow Program has been designed so that instream flow studies may be conducted by qualified third parties with the Agencies' oversight. In that event, this document will serve as a general overview of the requirements of such a study. This document does not provide sufficient guidance to meet all the varied conditions that may be encountered in Texas. Those conducting studies should communicate with the Agencies before modifying or adopting the methods described in this document.

13 *Acknowledgments*

This document represents the collective effort of many former and current staff members of the Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board. The list of those who contributed by writing, reviewing, editing, or illustrating the text is too lengthy to present here. But the Agencies are truly appreciative of their efforts. Overseeing boards and commissions and executive directors/administrators of the Agencies contributed to the quality of this document by supporting the efforts of the Texas Instream Flow Program and authorizing the National Research Council review of the program.

The National Research Council's review of the Texas Instream Flow Program, including a draft version of this document, was insightful and very beneficial for further development. In a similar manner, comments and feedback from many others outside the Agencies improved this document. Staff of other state and federal agencies, river authorities, and universities, members of the public, and other stakeholders all took the time to review earlier drafts of this document and provide feedback in writing or in person. The Agencies appreciate their interest and assistance in improving the Texas Instream Flow Program.

14 *References*

Aadland, L.P, 1993, Stream habitat types—their fish assemblages and relationship to flow: North American Journal of Fisheries Management, v. 13, p. 790–806.

ADWHA (Australian Department of Environment, Water, Heritage and the Arts), 2008, Murray-Darling Basin, www.environment.gov.au/water/mdb/index.html

Anderson, A.A., Hubbs, C., Winemiller, K.O., and Edwards, R.J., 1995, Texas freshwater fish assemblages following three decades of environmental change: Southwest Naturalist, v. 40, p. 314–321.

Angermeier, P.L., 1987, Spatiotemporal variation in habitat selection by fishes in small Illinois streams, in Matthews, W.J., and Heins, D.C., eds., Community and evolutionary ecology of North American stream fishes: Norman, Oklahoma, University of Oklahoma Press, p. 52–60.

Annear, T., Chisholm, I, Beecher, H., Locke, A., and others, 2004, Instream flows for riverine resource stewardship, revised edition: Cheyenne, Wyoming, Instream Flow Council.

Arcement, G.R., and Schneider, V.R., 1989, Guide for selecting Manning's roughness coefficients for natural channels and floodplains: U.S. Geological Survey Water-Supply Paper 2339, www.fhwa.dot.gov/bridge/wsp2339.pdf

Armour, C.L., 1991, Guidance for evaluating and recommending temperature regimes to protect fish: U.S. Fish and Wildlife Service Biological Report 90(22), 13 p.

Arthington, A., Brizga, S., and Kennard, M., 1998, Comparative evaluation of environmental flow assessment techniques—best practice framework: Canberra, Australia, Land and Water Resources Research and Development Corporation, Occasional Paper 25/98, www.lwa.gov.au/downloads/publications_pdf/PR980305.pdf

Austin, B., and Wentzel, M., 2001, Two-dimensional fish habitat modeling for assessing instream flow requirements: Integrated Water Resources Management, v. 272, p. 393–399.

Bain, M.B., and Knight, J.G., 1996, Classifying stream habitat using fish community analysis, in Leclerc, M., Capra, H., Valentine, S., Boudreault, A., and Cote, Y., eds., Ecohydraulics 2000: Proceedings of the second international symposium on habitat hydraulics: Quebec, Canada, INRS-Eau, Co-published with FQSA, IAHR/AIRH, p. B107–B117.

Baker, V.R., 1977, Stream channel response to floods, with examples from central Texas: Geological Society of America Bulletin 88, p.1057–71.

Bartholow, J.M., 1989, Stream temperature investigations: field and analytical methods: U.S. Fish and Wildlife Service Biological Report 89(17), Instream Flow Information Paper 13, www.krisweb.com/biblio/gen_usfws_bartholow_1989_br8917.pdf

Bates, P.D., Anderson, M.G., Hervouet, J.M., and Hawkes, J.C., 1997, Investigating the behavior of two-dimensional finite element models of compound channel flow: Earth Surfaces and Landforms, v. 22. p. 3–17.

Beard, L., 1975, Generalized evaluation of flash flood potential: Austin, Texas, Center for Research in Water Resources Report CRWR-124.

BEG (Bureau of Economic Geology), 1992, Geology of Texas (map), www.lib.utexas.edu/geo/geologic_maps.html

BEG (Bureau of Economic Geology), 1996a, Physiographic map of Texas, www.lib.utexas.edu/geo/geologic_maps.html

BEG (Bureau of Economic Geology), 1996b, River basin map of Texas, www.lib.utexas.edu/geo/geologic_maps.html

BEG (Bureau of Economic Geology), 1999, Land-resource map of Texas, www.lib.utexas.edu/geo/geologic_maps.html

BEG (Bureau of Economic Geology), 2000, Vegetation/cover types of Texas (map), www.lib.utexas.edu/geo/geologic_maps.html

Benda, L., Poff, L.,Tague, C., Palmer, M., Pizzuto, J., Cooper, S., Stanley, E. and Moglen, G., 2002, How to avoid train wrecks when using science in environmental problem solving: BioScience, v. 52, no. 12, p. 1127–1136.

Bethemont, J., Andriamahefa, H., Rogers, C., and Wasson, J.G., 1996, Une approche régionale de la typologie morphologique des cours d'eau—application de la méthode “morphorégions” au bassin de la Loire et perspectives pour le bassin du Rhône (France): Revue de Géographie de Lyon, v. 71, p. 311–322.

Bovee, K.D., 1986, Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology: U.S. Fish and Wildlife Service Instream Flow Information Paper 21 FWS/OBS-86/7.

Bovee, K.D., 1996, Perspectives on two-dimensional river habitat models—the PHABSIM experience, in Leclerc, M., Capra, H., Valentine, S., Boudreault, A., and Cote, Y., eds., Ecohydraulics 2000: Proceedings of the second international symposium on habitat hydraulics, Quebec, Canada, INRS-Eau, Co-published with FQSA, IAHR/AIRH.

Bovee, K.D., Lamb, B.L., Bartholow, J.M., Stalnaker, C.D., Taylor, J., and Henriksen, J., 1998, Stream habitat analysis using the Instream Flow Incremental Methodology: U.S. Geological Survey Information and Technical Report USGS/BRD-1998-0004, www.mesc.usgs.gov/products/Publications/3910/preface.html

Bovee, K.D., Newcomb, T.J., and Coon, T.G., 1994, Relations between habitat variability and population dynamics of bass in the Huron River, Michigan: National Biological Survey Biological Report No. 21, www.fort.usgs.gov/products/publications/2486/2486.pdf

Bowen, Z.H., Bovee, K.D., and Waddle, T.J., 2003, Effects of flow regulation on shallow-water habitat dynamics and floodplain connectivity: Transactions of the American Fisheries Society, v. 132, p. 809–823.

Bowen, Z.H., Freeman, M.C., and Bovee, K.D., 1998, Evaluation of generalized habitat criteria for assessing impacts of altered flow regimes on warmwater fishes: Transactions of the American Fisheries Society, v. 127, p. 455–468.

Bradley, C.B., and Smith, D.G., 1984, Meandering channel response to altered flow regime—Milk River, Alberta and Montana: Water Resources Research, v. 20, p. 1913–1920.

Brandt, S.A., 2000, Classification of geomorphologic effects downstream of dams: Catena, v. 40, p. 325–401.

Brierley, G.J., and Fryirs, K., 2000, River styles—a geomorphic approach to catchment characterization—implications for river rehabilitation in Bega catchment, New South Wales, Australia: Environmental Management, v. 25, no. 6, p. 661–679.

Brierley, G.J., and Fryirs, K., 2005, Geomorphology and river management—applications of the River Styles framework: Oxford, England, Blackwell Publishing.

Brown, C., and King, J., 2003, Environmental flows—concepts and methods: The World Bank water resources and environment technical note C.1., www.iucn.org/places/medoffice/cdflow/conten/5/pdf/5-3-International-Guid/World-Bank-ENG/Environmental-Flows/NoteC1Environme.pdf

Brune, G., 1981, Springs of Texas: Arlington, Texas, Gunnar Brune.

Brune, G.M., 1953, Trap efficiency of reservoirs: Transactions America Geophysical Union, v. 34, p. 407–18.

Brunner, G.W., 2002, HEC-RAS—river analysis system hydraulic reference manual, CPD-69: Davis, California, U.S. Army Corps of Engineers Hydrologic Engineering Center, www.hec.usace.army.mil/software/hec-ras/documents/hydref/index.html

Brussock, P.P., Brown, A.V., and Dixon, J.C., 1985, Channel form and stream ecosystem models: Water Resources Bulletin, v. 21, p. 859–866.

Bunn, S.E., and Arthington, A.H., 2002, Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity: Environmental Management, v. 30, p. 492–507.

Bunte, K., and Abt, S.R., 2001, Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-74, www.fs.fed.us/rm/pubs/rmrs_gtr74.html

Busch, D.E., Ingraham, N.L., and Smith, S.D., 1992, Water uptake in woody riparian phreatophytes of the southwestern United States—a stable isotope study: Ecological Applications, v. 2, p. 450–459.

Busch, D.E. and Scott, M.L., 1995, Western riparian ecosystems, in LaRoe, E.T., Farris, G.S., Puckett, C.E., Doran, P.D., and Mac, M.J., eds., Our living resources—a report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems: U.S. Department of the Interior, National Biological Service, p. 286–290, www.mesc.usgs.gov/Products/Publications/pub_abstract.asp?PubID=3068

Capra, H., Breil, P., and Souchon, Y., 1995, A new tool to interpret magnitude and duration of fish habitat variations: Regulated Rivers—Research and Management, v. 10, p. 281–289.

Carter, G.S., and Shankar, U., 1997, Creating rectangular bathymetry grids for environmental numerical modeling of gravel-bed rivers: Applied Mathematical Modelling, v. 21, p. 699–708.

Castleberry, D.T., Cech, J.J., Jr., Erman, D.C., Hankin, D., Healey, M., Kondolf, G.M., Mangel, M., Mohr, M., Moyle, P.B., Nielsen, J., Speed, T.P., and Williams, J.G., 1996, Uncertainty and instream flow standards: Fisheries, v. 21, no. 8, p. 20–21.

Chow, V.T., ed., 1964, Handbook of applied hydrology: New York, McGraw-Hill.

Collier, M., Webb, R.H., and Schmidt, J.C., 1996, Dams and rivers: a primer on the downstream effects of dams: U.S. Geological Survey Circular 1126, pubs.er.usgs.gov/usgspubs/cir/cir1126

Collier, M.P., Webb, R.H., and Schmidt, J.C., 2000, Dams and rivers: a primer on the downstream effects of dams (2d ed): U.S. Geological Survey Circular 1126.

Conner, J.V., and Suttkus, R.D., 1986, Zoogeography of freshwater fishes of the western gulf slope of North America, in Hocutt, C.H., and Wiley, E.O., eds., The zoogeography of North American freshwater fishes: New York, John Wiley and Sons, p. 413–456.

CRCFE (Cooperative Research Centre for Freshwater Ecology), 2001, Development of a framework for the sustainable rivers audit: Canberra, Australia, Cooperative Research Centre for Freshwater Ecology, Technical Report 8/2001, pandora.nla.gov.au/tep/24782

Crowder, D.W., and Diplas, P., 2000, Using two-dimensional hydrodynamic models at the scales of ecological importance: Journal of Hydrology, v. 230, p. 172–191.

Dale, V.H., and Beyeler, S.C., 2001, Challenges in the development and use of ecological indicators: Ecological Indicators, v. 1, p. 3–10.

Deering, M.K., 1990, Practical applications of 2-D hydrodynamic modeling, in Chang, H.H., and Hill, J.C., eds., Hydraulic engineering—proceedings of the 1990 national conference: New York, American Society of Civil Engineers.

Donnell, B.P., Letter, J.V., McAnally, W.H., and others, 2001, User's guide for RMA-2 Version 4.5: U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.

Edwards, R.J., Longley, G., Moss, R., Ward, J., Matthews, R., and Stewart, B., 1989, A classification of Texas aquatic communities with special consideration toward the conservation of endangered and threatened taxa: The Texas Journal of Science, v. 41, p. 231–240.

Elwood, J.W., Newbold, J.D., O'Neill, R.V., and Van Winkle, W., 1983, Resource spiralling—an operational paradigm for analyzing lotic ecosystems, in Fontaine, T.D., III., and Bartell, S.M., eds., Dynamics of lotic ecosystems: Ann Arbor, Ann Arbor Science, p. 3–27.

EMSI (Environmental Modeling Systems, Inc.), 2005, Online help reference for surface water modeling system, EMSI, Provo, Utah, ems-i.com/SMS/sms_help_frameset.html

Fausch, K.D., Torgersen, C.E., Baxter, C.V., and Li, H.W., 2002, Landscapes to riverscapes— bridging the gap between research and conservation of stream fishes: BioScience, v. 52, no. 6, p. 483–498.

Finnie, J., Donnell, B., Letter, J., and Bernard, R.S., 1999, Secondary flow correction for depth-averaged flow calculations: Journal of Engineering Mechanics, v. 125, p. 848–863.

FISRWG (Federal Interagency Stream Restoration Working Group), 1998, Stream corridor restoration—principles, processes, and practices: GPO Item No. 0120-A; SuDocs No. A 57.6/2EN3/PT.653, www.nrcs.usda.gov/Technical/stream_restoration/newtofc.htm

Franke, R., 1982, Scattered data interpolation—tests of some methods: Mathematics of Computation, v. 38, p. 181–200.

Freeman, G.E., 1992, Solving the dilemma: to wave or to oscillate? Opposing formulations of the shallow water equations in river modeling: College Station, Texas, Texas A&M University, PhD dissertation.

Freeman, M.C., Bowen, Z.H., and Bovee, K.D., 1999, Transferability of habitat suitability criteria: North American Journal of Fisheries Management, v. 19, p. 626–628.

Freeman, M.C., Bowen, Z.H., Bovee, K.D., and Irwin, E.R., 2001, Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes: Ecological Applications, v. 11, p. 179–190.

Freese and Nichols, Inc., 2005, Lake Columbia downstream impacts analysis: Report prepared for the Angelina and Neches River Authority and Texas Water Development Board, www.twdb.state.tx.us/RWPG/rpgm_rpts/2001483385DOWNSTREAM%20IMPACTS.pdf

Friedman, J.M., Osterkamp, W.R., Scott, M.L., and Auble, G.T., 1998, Downstream effects of dams on channel geometry and bottomland vegetation—regional patterns in the Great Plains: Wetlands, v. 35, p. 619–633.

Frissell, C.A., Liss, W.J., Warren, C.E., and Hurley, M.D., 1986, A hierarchical framework for stream habitat classification—viewing streams in a watershed context: Environmental Management, v. 10, p. 199–214.

Gergel, S.E., Turner, M.G., Miller, J.R., Melack, J.M., and Stanley, E.H., 2002, Landscape indicators of human impacts to riverine systems: Aquatic Sciences, v. 64, p. 118–128.

Giller, P., 2005, River restoration—seeking ecological standards: Journal of Applied Ecology, v. 42, p. 201–207, www.restoringrivers.org/PDF/standards/GillerIntroduction.pdf

Gold, A.J., and Kellogg, D.Q., 1997, Modeling internal processes of riparian buffer zones, in Haycock, N., Burl, T., Goulding, K., and Dinay, G., eds., Buffer zones—their processes and potential in water protections: Harpenden, England, Quest Environmental, p. 192–207.

Gordon, R.L., 1989, Acoustic measurement of river discharge: Journal of Hydraulic Engineering, v. 115, p. 925–936.

Gore, J.A., Layzer, J.B., and Mead, J., 2001, Macroinvertebrate instream flow studies after 20 years—a role in stream management and restoration: Regulated Rivers—Research and Management, v. 17, p. 527–542.

Gorman, O.T., and Karr, J.R., 1978, Habitat structure and stream fish communities: Ecology, v. 59, p. 507–515.

Graf, W.L., 1999, Dam nation—a geographic census of American dams and their large-scale hydrologic impacts: Water Resources Research, v. 35, p. 1305–1311.

Graf, W.L., 2001, Damage control—restoring the physical integrity of America's rivers: Annals of the Association of American Geographers, v. 91, p. 1–27.

Gregory, S.V., Swanson, F.J., McKee, W.A., and Cummins, K.W., 1991, An ecosystem perspective of riparian zones: BioScience, v. 41, p. 540–551.

Harby, A., Baptist, M., Dunbar, M., and Schmutz, S., eds., 2004, State-of-the-art in data sampling, modeling, analysis and applications of river habitat modeling: COST Action 626, European Aquatic Modelling Network.

Hardison, B.S., and Layzer, J.B., 2001, Relations between complex hydraulics and the localized distribution of mussels in three regulated rivers: Regulated Rivers—Research and Management, v. 17, p. 77–84.

Hardy, T.B., 1998, The future of habitat modeling and instream flow assessment techniques: Regulated Rivers—Research and Management, v. 14, p. 405–420.

Harwell, M.A., Myers, V., Young, T., Bartuska, A., and Gassman, N., 1999, A framework for an ecosystem integrity report card: BioScience, v. 49, p. 543–556.

HEC (Hydrologic Engineering Center), 2005, Hydrologic Modeling System HEC-HMS users manual, Version 3.0, CPD-74A: U.S. Army Corps of Engineers-HEC, Sacramento, California, www.hec.usace.army.mil/software/hec-hms/documentation/CPD-74A_2005Dec.pdf

Henriksen, J.A., Heasley, J., Kennen, J.G., and Nieswand, S., 2006, Users' manual for the Hydroecological Integrity Assessment Process software (including the New Jersey Assessment Tools): U.S. Geological Survey, www.fort.usgs.gov/products/publications/21598/21598.pdf

Hodges, B.R., and Imberger, J., 2001, Simple curvilinear method for numerical methods of open channels: Journal of Hydraulic Engineering, v. 127, p. 949–958.

Howells, R.G., Neck, R.W., and Murray, H.D., 1996, Freshwater mussels of Texas: Texas Parks and Wildlife Department.

Hubbs, C., Marsh-Matthews, E., Matthews, W.J., and Anderson, A.A., 1997, Changes in fish assemblages in East Texas streams from 1953 to 1986: The Texas Journal of Science, Supplement-Invited Symposium, v. 49, p. 67–84.

Hubbs, C., Edwards, R.J., and Garrett, G.P., 1991, An annotated checklist of the freshwater fishes of Texas, with keys to identification of species: Texas Journal of Science, Supplement, v. 43, p. 4.

Huckleberry, G., 1994, Contrasting channel responses to floods on the middle Gila River, Arizona: Geology, v. 22, p. 1083–1086.

Imhof, J., Fitzgibbon, J., and Annable, W., 1996, A hierarchical evaluation system for characterizing watershed ecosystems for fish habitat: Canadian Journal of Fisheries and Aquatic Science, v. 53 (supplemental 1), p. 312–326.

Johnston, C.E., 1999, The relationship of spawning mode to conservation of North American minnows (Cyprinidae): Environmental Biology of Fishes, v. 55, p. 21–30.

Johnson, L.B., and Gage, S.H., 1997, Landscape approaches to the analysis of aquatic ecosystems: Freshwater Biology, v. 37, p. 113–132.

Johnson, S.L., and Covich, A.P., 2000, The importance of night-time observations for determining habitat preferences of stream biota: Regulated Rivers—Research and Management, v. 16, p. 91–99.

Jowett, I.G., 1993, A method for objectively identifying pool, run, and riffle habitats from physical measurements: New Zealand Journal of Marine and Freshwater Research, v. 27, p. 241–248.

Junk, W.J., Bayley, P.B., and Sparks, R.E., 1989, The flood pulse concept in river-floodplain systems, in Dodge, D.P., ed., Proceedings of the international large river symposium, special publication: Canadian Journal of Fisheries and Aquatic Sciences, v. 106, p. 110–127.

Juracek, K., 2000, Channel stability downstream from a dam assessed using aerial photographs and stream-gage information: Journal of the American Water Resources Association, v. 36, no. 3, p. 633–645.

Kiesling, R.L., and Flowers, J.D., 2002, Trinity River in-stream flow study, Phase I final project report to Texas Natural Resource Conservation Commission, contract no. 582-0-34033: Stephenville, Texas, Tarleton State University, Texas Institute for Applied Environmental Research.

King, I.P., 1982, A three dimensional finite element model for stratified flow, in Finite elements in water resources, Proceedings of the 4th International Conference: New York, Springer-Verlag.

King, I.P., 1992, Evaluation of modeling parameters for simulation of estuarial systems, in Spaulding, M.L., Bedford, K., Blumberg, A., Cheng, R., and Swanson, C., eds., Estuarine and coastal modeling, Proceedings of the 2nd International Conference: New York, American Society of Civil Engineers.

King, I.P., Norton, W.R., and Iceman, K.R., 1975, A finite element solution for two-dimensional stratified flow problems, in Gallagher, R.H., Oden, J.T., Taylor, C., and Zienkiewicz, O.C., eds., Finite elements in fluids, v. 1: New York, John Wiley and Sons.

King, J., and Brown, C., 2003, Environmental flows—case studies: The World Bank, Water resources and environment technical note C.2, www.iucn.org/places/medoffice/cdflow/conten/5/pdf/5-3-International-Guid/World-Bank-ENG/Environmental-Flows/NoteC2Environme.pdf

King, J., Tharme, R., and Brown, C., 1999, Thematic report, definition and implementation of instream flows: Cape Town, South Africa, World Commission on Dams, www.dams.org/docs/kbase/contrib/env238.pdf

Knighton, D., 1984, Fluvial forms and processes: Baltimore, Maryland, Edward Arnold.

Kondolf, G., Montgomery, D., Piegay, H., and Schmitt, L., 2003, Geomorphic classification of rivers and streams, in Tools in fluvial geomorphology, eds., Kondolf, G., and Piegay, H.: Chichester, England, John Wiley and Sons.

Kondolf, M., 1998, Lessons learned from river restoration projects in California: Aquatic Conservation—Marine and Freshwater Ecosystems, v. 8, p. 39–52.

Lane, E.W., 1955, The importance of fluvial morphology in hydraulic engineering: Proceedings of the American Society of Civil Engineering, v. 81, p. 1–17.

Lane, S.N., Bradbrook, K.F., Richards, K.S., Biron, P.A., and Roy, A.G., 1999, The application of computational fluid dynamics to natural river channels—three-dimensional versus two-dimensional approaches: Geomorphology, v. 29, p. 1–20.

Leclerc, M.A., Boudreault, J.A., Bechara, J.A., and Corfa, G., 1995, Two-dimensional hydrodynamic modeling—a neglected tool in the instream flow incremental methodology: Transactions of the American Fisheries Society, v. 124, p. 645–662.

Leonard, P.M. and Orth, D.J., 1988, Use of habitat guilds to determine instream flow requirements: North American Journal of Fisheries Management, v. 8, p. 399–409.

Leopold, L.B., and Wolman, M.G., 1957, River channel patterns—braided, meandering, and straight: U.S. Geological Survey Professional Paper 282-B.

Linam, G.W., Kleinsasser, L.J., and Mayes, K.B., 2002, Regionalization of the index of biotic integrity for Texas streams: Texas Parks and Wildlife Department, River Studies Report 17, www.tpwd.state.tx.us/publications/pwdpubs/media/pwd_rp_t3200_1086.pdf

Longley, G., Butler, L. Creutzburg, B., Mosely, J., and Stanley, C., 1997, IFIM-Phase I study, Guadalupe River, Report to the Guadalupe-Blanco River Authority: San Marcos, Texas, Southwest Texas State University, Edwards Aquifer Research and Data Center.

Lotspeich, F.B., 1980. Watersheds as the basic ecosystem—this conceptual framework provides a basis for a natural classification system: Water Resource Bulletin, v. 16, no. 4, p. 581–586.

Lytle, D.A., and Merritt, D.M., 2004, Hydrologic regimes and riparian forests—a structured population model for cottonwood: Ecology, v. 85, p. 2493–2503.

Madej, M.A., 1999, What can thalweg profiles tell us? A case study from Redwood Creek, California: Watershed Management Council Networker, v. 8, no. 4, watershed.org/news/sum_99/11_thalweg_profiles.htm

Mathews, R.C., Jr., and Tallent, J.R., 1996, Instream flow assessment for the Sandies Creek Reservoir site, potential reservoir project identified in the Texas Water Plan, final report: Texas Water Development Board.

Matsumoto, J., 1995, User's manual for the TWDB's rainfall-runoff model: Texas Water Development Board.

McGarigal, K., and Marks, B.J., 1995, FRAGSTATS—spatial pattern analysis program for quantifying landscape structure: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-351, www.fs.fed.us/pnw/pubs/gtr_351.pdf

MDBC (Murray-Darling Basin Commission), 2003a, Fish theme summary of pilot audit technical report: Canberra, Australia, Murray-Darling Basin Commission Publication 06/04, www.mdbc.gov.au/__data/page/64/Web_Summary_Fish_Theme.pdf

MDBC (Murray-Darling Basin Commission), 2003b, Hydrology theme pilot audit technical report—sustainable rivers audit: Canberra, Australia, Murray-Darling Basin Commission Publication 08/04, www.mdbc.gov.au/__data/page/64/summary_hydrology_theme.pdf

MDBC (Murray-Darling Basin Commission), 2003c, Macroinvertebrate theme pilot audit technical report—sustainable rivers audit: Canberra, Australia, Murray-Darling Basin Commission Publication 07/04, www.mdbc.gov.au/__data/page/64/summary_macroinvert_theme.pdf

MDBC (Murray-Darling Basin Commission), 2005a, The Barmah-Millewa Forest asset environmental management plan 2005/2006: Canberra, Australia, Murray-Darling Basin Commission Publication 31/05, www.thelivingmurray.mdbc.gov.au/__data/page/246/BM_AEMP_text_final.pdf

MDBC (Murray-Darling Basin Commission), 2005b, The River Murray channel asset environmental management plan 2005/2006: Murray-Darling Basin Commission, Canberra, Australia, Publication 30/05, www.thelivingmurray.mdbc.gov.au/__data/page/251/RMC_AEMP_final.pdf

MEA (Millennium Ecosystem Assessment), 2005, Ecosystems and human well-being—wetlands and water, synthesis: Washington, D.C., World Resources Institute, www.millenniumassessment.org/documents/document.358.aspx.pdf

Melanson, G.P., 1993, Riparian landscapes: Cambridge, England, Cambridge University Press.

Merritt, R.W., and Cummins, K.W., eds., 1996, An introduction to the aquatic insects of North America, 3rd ed.: Dubuque, Iowa, Kendall/Hunt Publishing Co., 862 p.

Milhouse, R.T., 1998, Modelling of instream flow needs—the link between sediment and aquatic habitat: Regulated Rivers—Research and Management, v. 14, p. 79–94.

Montgomery, D., and Buffington, J., 1998, Channel process, classification and response, in River Ecology and Management—Lessons from the Pacific Coastal Ecoregion, eds., Naiman, R., and Bilby, R.: New York, Springer-Verlag.

Mosier, D.T., and Ray, R.T., 1992, Instream flows for the lower Colorado River—reconciling traditional beneficial uses with the ecological requirements of the native aquatic community: Austin, Texas, Lower Colorado River Authority.

Moyle, P.B., Marchetti, M.P., Balrige, J., and Taylor, T.L., 1998, Fish health and diversity—justifying flows for a California stream: Fisheries, v. 23, no. 7, p. 6–15.

Nanson, G.C., and Knighton, A.D., 1996, Anabranching rivers—their cause, character, and classification: Earth Surface Processes and Landforms, v. 21, p. 217–239.

Newbold, J.D., Elwood, J.W., O'Neill, R.V., and Van Winkle, W., 1981, Nutrient spiralling in streams—the concept and its field measurements: Canadian Journal of Fisheries and Aquatic Sciences, v. 38, p. 860–863.

Nilsson, C., and Svedmark, M., 2002, Basic principles and ecological consequences of changing water regimes—riparian plant communities: Environmental Management, v. 30, p. 468–480.

Nislow, K., Magilligan, F., Fassnacht, H., Bechtel, D., and Ruesink, A., 2003, Effects of dam impoundment on the flood regime of natural floodplain communities in the Upper Connecticut River: Journal of the American Water Resources Association, v. 38, no. 6, p. 1533–1548.

NRC (National Research Council), 2005, The science of instream flows—A review of the Texas Instream Flow Program: Washington, D.C., National Academies Press, books.nap.edu/catalog/11197.html

NRC (National Research Council), 2002, Riparian areas—functions and strategies for management: Washington, D.C., National Academy Press, www.nap.edu/books/0309082951/html

NRCS (National Resources Conservation Service), 2006, National coordinated common resource area geographic database, soils.usda.gov/survey/geography/cra.html

NSWDECC (New South Wales Department of Environment and Climate Change), 2008, Murray River catchment water quality objectives explained, www.epa.nsw.gov.au/ieo/Murray/report-03.htm

Orth, D.J., 1987, Ecological considerations in the development and application of instream flow-habitat models: Regulated Rivers—Research and Management, v. 1, p. 171–181.

Osting, T.D., Mathews, R.C., and Austin, B.N., 2004a, Analysis of instream flows for the lower Brazos River—Hydrology, hydraulics, and fish habitat utilization: Texas Water Development Board, hyper20.twdb.state.tx.us/data/Inflow/Brazos04/LowBrazos2004.htm

Osting, T.D., Mathews, R.C., and Austin, B.N., 2004b, Analysis of instream flows for the Sulphur River—Hydrology, hydraulics, and fish habitat utilization: Texas Water Development Board, hyper20.twdb.state.tx.us/data/Inflow/Sulphur04/Sulphur2004.html

Palmer, M., Hart, D., Allan, D., Bernhardt, E., and the National Riverine Restoration Science Synthesis Working Group, 2003, Bridging engineering, ecological, and geomorphic science to enhance riverine restoration: local and national efforts, in Proceedings, A National Symposium on Urban and Rural Stream Protection and Restoration, EWRI World Water and Environmental Congress: Reston, Virginia, American Society of Civil Engineers.

Palmer, M., Bernhardt, E., Allan, J., Lake, P., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad Shah, J., Galat, D., Loss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Kondolf, G., Lave, R., Meyer, J., O'Donnell, T., Pagano, L., and Sudduth, E., 2005, Standards for ecologically successful river restoration: Journal of Applied Ecology, v. 42, p. 208–217.

Pardo, I., and Armitage, P.D., 1997, Species assemblages as descriptors of mesohabitats: Hydrobiologia, v. 344, p. 111–128.

Parrott, H., Marion, D.A., and Perkinson, R.D., 1989, A four-level hierarchy for organizing wildland stream resource information, in Headwater Hydrology—proceedings of the 1989 symposium of the AWRA: Bethesda, Maryland, American Water Resources Association.

Pennak, R.W., 1989, Fresh-water invertebrates of the United States, 3rd ed.: New York, John Wiley and Sons.

Peterson, J., and Rabeni, C.F., 1995, Optimizing sampling effort for sampling warmwater stream fish communities: North American Journal of Fisheries Management, v. 15, p. 528–541.

Petts, G.E., 1979, Complex response of river channel morphology to reservoir construction: Progress in Physical Geography, v. 3, p. 329–62.

Philip Williams and Associates, 2003, An environmental alternative for the Pajaro River flood plan, San Francisco, California.

Phillips, J.D., 2003, Toledo Bend Reservoir and geomorphoric response in the lower Sabine River: River Research and Applications, v. 19, p. 137–159.

Phillips, J.D., and Musselman. Z.A., 2003, The effect of dams on fluvial sediments delivery to the Texas coast in Proceedings of Coastal Sediments 2003: New York, American Society of Civil Engineers.

Phillips, J.D., Slattery, M.C., and Musselman, Z.A., 2004, Dam-to-delta sediment inputs and storage in the lower Trinity River: Geomorphology, v. 62, p. 17–34.

Phillips, J., Slattery, M., and Musselman, Z., 2005. Channel adjustments of the lower Trinity River, Texas, downstream of Livingston Dam: Earth Surface Processes and Landforms, v. 30, p. 1419–1439.

Poff, N.L., 1997, Landscape filters and species traits—towards mechanistic understanding and predication in stream ecology: Journal of the North American Benthological Society, v. 16, p. 391–409.

Poff, N.L., and Ward, J.V., 1989, Implications of streamflow variability and predictability for lotic community structure—a regional analysis of streamflow patterns: Canadian Journal of Fisheries and Aquatic Sciences, v. 46, p. 1805–1818.

Poff, N.L., and Ward, J.V., 1990, Physical habitat template of lotic systems—recovery in the context of historical pattern of spatiotemporal heterogeneity: Environmental Management, v. 14, p. 629–645.

Power, M.E., 1984, Depth distributions of armored catfish—predator-induced resource avoidance: Ecology, v. 65, p. 523–528.

Prasuhn, A.L., 1987, Fundamentals of hydraulic engineering: Ft. Worth, Texas, Harcourt, Brace, and Jovanovich, Inc.

Railsback, S., 1999, Reducing uncertainties in instream flow studies: Fisheries, v. 24, no. 4, p. 24–26.

Raven, P.J., Boon, P.J., Dawson, F.H., and Ferguson, A.J.D., 1998, Towards an integrated approach to classifying and evaluating rivers in the UK: Aquatic Conservation-Marine and Freshwater Ecosystems, v. 8, p. 383–393.

Reeves, G.H., Everest, F.H., and Sedell, J.R., 1993, Diversity of juvenile salmonid assemblages in coastal Oregon basins with different levels of timber harvest: Transactions of the American Fisheries Society, v. 122, p. 309–317.

Reid, L.M., and Dunne, T., 1996, Rapid evaluation of sediment budgets: Reiskirchen, Germany, Catena Verlag.

Richards, D.R., 1990, Flow separation around a solitary dike—eddy viscosity and mesh considerations, in Chang H.W., and Hill, J.C., eds., Hydraulic engineering—Proceedings of the 1990 National Conference: New York, American Society of Civil Engineers.

Richter, B., Mathews, R., Harrison, D., and Wigington, R., 2003, Ecologically sustainable water management—managing river flows for ecological integrity: Ecological Applications, v. 13, no. 1, p. 206–224.

Richter, B.D., Baumgartner, J.V., Powell, J., and Braun, D.P., 1996, A method for assessing hydrologic alteration within ecosystems: Conservation Biology, v. 10, p. 1163–1174.

Richter, B.D., Baumgartner, J.V., Wigington, R., and Braun, 1997, How much water does a river need: Freshwater Biology, v. 37, p. 231–249.

Robinson, C.T., Tockner, K., and Ward, J.V., 2002, The fauna of dynamic riverine landscapes: Freshwater Biology, v. 47, p. 661–677.

Rosgen, D.L., 1996, Applied river morphology: Pagosa Springs, Colorado, Wildland Hydrology.

Rosgen, D.L., 2001, A stream channel stability assessment methodology: Proceedings of the 7th Federal Interagency Sedimentation Conference, Reno, Nevada, v. 2, p. 18–26.

Rowntree, K.M., and Wadeson, R.A., 1998, A geomorphological framework for the assessment of instream flow requirements: Aquatic Ecosystem Health and Management, v. 1, p. 125–141.

Rutherfurd, I., Jerie, K., and Marsh, N., 2000, A rehabilitation manual for Australian streams, v. 1: Canberra, Australia, Land and Water Resources Research and Development Corporation, www.lwa.gov.au/downloads/publications_pdf/PR000324.pdf

Salafsky N., Margoluis, R., and Redford, K.H., 2001, Adaptive management—a tool for conservation practitioners: Washington, D.C., Biodiversity Support Program, fosonline.org/Site_Docs/AdaptiveManagementTool.pdf

Sansom, A., 1995, Texas lost—vanishing heritage: Dallas, Texas, Parks and Wildlife Foundation, Inc.

Saunders, K.S., Mayes, K.B., Jurgensen, T.A., Trungale, J.F., Kleinsasser, L.J., Aziz, K., Fields, J.R., and Moss, R.E., 2001, An evaluation of spring flows to support the upper San Marcos River spring ecosystem, Hays County, Texas: Texas Parks and Wildlife Department Texas River Studies Report 16, www.tpwd.state.tx.us/publications/pwd-pubs/media/pwd_rp_t3200_1087.pdf

Schlosser, I.J., 1982, Fish community structure and function along two habitat gradients in a headwater stream: Ecological Monographs, v. 52, p. 395–414.

Schofield, N., Burt, A., and Connell, D., 2003, Environmental water allocation—principles, Canberra, Australia practices, policies, progress and prospects: Canberra, Austrailia, Land and Water Australia, Product number PR030541, www.lwa.gov.au/downloads/publications_pdf/PR030541.pdf

Stalnaker, C.B., Bovee, K.D., and Waddle, T.J., 1996, Importance of the temporal aspects of habitat hydraulics to fish population studies: Regulated Rivers—Research and Management, v. 12, p. 145–153.

Stanford, J.A., and Ward, J.V., 1993, An ecosystem perspective of alluvial rivers—connectivity and the hyporheic corridor: Journal of the North American Benthological Society, v. 12, p. 48–60.

Statzner, B., and Müller, R., 1989, Standard hemispheres as indicators of flow characteristics in lotic benthic research: Freshwater Biology, v. 21, p. 445–459.

Stazner, B., and Higler, B., 1986, Stream hydraulics as a major determinant of benthic invertebrate zonation patterns: Freshwater Biology, v.16, p. 127–139.

Stein, B., 2002, States of the union—ranking America's biodiversity: Arlington, Virginia, NatureServe, www.natureserve.org/publications/statesUnion.jsp

Tabacchi, E., 2005, Vegetation patterns and ecological dynamics along narrow riparian zones, in Petts, G., and Kennedy, R., eds., Emerging concepts for integrating human and environmental water needs in river basin management, ERDC/EL TR-05-13: U.S. Army Corps of Engineers, p. 66–71, el.erdc.usace.army.mil/elpubs/pdf/trel05-13.pdf

TCEQ (Texas Commission on Environmental Quality), 2004a, Water quality program and assessment summary, www.tceq.state.tx.us/compliance/monitoring/water/quality/data/04twqi/twqi04.html

TCEQ (Texas Commission on Environmental Quality), 2004b, Atlas of Texas Surface Waters, GI-316, www.tceq.state.tx.us/comm_exec/forms_pubs/pubs/gi/gi-316/index.html

Thorne, C., 1997, Channel types and morphological classification, in Applied Fluvial Geomorphology for River Engineering and Management, eds., Thorne, C., Hey, R., and Newson, M.: Chichester, England, John Wiley and Sons.

TIFP (Texas Instream Flow Program), 2002, Texas Instream Flow Studies: Programmatic Work Plan, www.twdb.state.tx.us/instreamflows/pdfs/Programmatic_Work_Plan.pdf

TNRCC (Texas Natural Resource Conservation Commission), 2000, Texas Surface Water Quality Standards, Chapter 307 of the Texas Administrative Code, adopted by the Texas Natural Resource Conservation Commission, July 26, 2000, www.tceq.state.tx.us/permitting/water_quality/wq_assessment/standards/WQ_standards_2000.html

TNRCC (Texas Natural Resource Conservation Commission), 1999, Receiving water assessment procedures manual, GI-253, www.tceq.state.tx.us/files/gi-253.pdf_4008532.pdf

Trush, W.J., McBain, S.M., and Leopold, L.B., 2000, Attributes of an alluvial river and their relation to water policy and management: Applied Physical Sciences, v. 97, no. 22, p. 11858–11863.

TWDB (Texas Water Development Board), 2007, Water for Texas—2007 State water plan, www.twdb.state.tx.us/publications/reports/State_Water_Plan/2007/2007StateWaterPlan/2007StateWaterPlan.htm

TWDB (Texas Water Development Board), 1990a, Major aquifers of Texas (map), www.lib.utexas.edu/geo/geologic_maps.html

TWDB (Texas Water Development Board), 1990b, Minor aquifers of Texas (map), www.lib.utexas.edu/geo/geologic_maps.html

USACE (U.S. Army Corps of Engineers), 1993, Engineering and design—river hydraulics, Engineering Manual EM1110-2-1416, www.usace.army.mil/publications/eng-manuals/em1110-2-1416

USSCS (U.S. Soil Conservation Service), 1982, Erosion and sedimentation by water in Texas: Texas Department of Water Resources Report 268.

Vadas, R.L., Jr., and Orth, D.J., 1998, Use of physical variables to discriminate visually determined mesohabitat types in North American streams: Rivers, v. 6, p. 143–159.

Vadas, R.L., Jr., and Orth, D.J., 2000, Habitat use of fish communities in a Virginia stream system: Environmental Biology of Fishes, v. 59, p. 253–269.

Vadas, R.L., Jr., and Orth, D.J., 2001, Formulation of habitat suitability models for stream fish guilds: do the standard methods work: Transactions of the American Fisheries Society, v. 130, p. 217–235.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., and Cushing, C.E., 1980, The river continuum concept: Canadian Journal of Fisheries and Aquatic Sciences, v. 37, p. 130–137.

Verstraeten, G, and Poesen, J., 2000, Estimating trap efficiency of small reservoirs and ponds: methods and implications for assessment of sediment yield: Progress in Physical Geography, v. 24, p. 219–51.

Waddle, T.J., ed., 2001, PHABSIM for Windows—user's manual and exercises: U.S. Geological Survey Open-File Report 01-340, www.fort.usgs.gov/products/publications/15000/15000.pdf

Wagner, M., 2004, Managing riparian habitats for wildlife: Texas Parks and Wildlife Department PWD BR W7000-306 (6/04), www.tpwd.state.tx.us/publications/pwdpubs/media/pwd_br_w7000_0306.pdf

Walters, R.A., 1995, Modeling surface water flow, in Carey, G.F., ed., Finite element modeling of environmental problems—surface and subsurface flow and transport: New York, John Wiley and Sons.

Ward, G.H., Jr., and Benaman, J., 1999a, A survey and review of modeling for TMDL application in Texas watercourses: Center for Research in Water Resources Report to Texas Natural Resource Conservation Commission.

Ward, G.H., Jr., and Benaman, J., 1999b. Models for TMDL application in Texas watercourses—screening and model review: Center for Research in Water Resources report to Texas Natural Resource Conservation Commission, Report No. CRWR-99-7, www.crwr.utexas.edu/reports/pdf/1999/rpt99-7.pdf

Ward, J.V., and Tockner, K., 2001, Biodiversity: towards a unifying theme for river ecology: Freshwater Biology, v. 46, p. 807–819.

Ward, J.V., Tockner, K., Arscott, D.B., and Claret, C., 2002, Riverine landscape diversity: Freshwater Biology, v. 47, p. 517–539.

Wiens, J.A., 2002, Riverine landscapes—taking landscape ecology into the water: Freshwater Biology, v. 47, p. 501–515.

Williams, G.P., 1978, Bankfull discharge of rivers: Water Resources Research, v. 14, p. 1141–58.

Williams, G.P., and Wolman, M.G., 1984, Downstream effects of dams on alluvial rivers: U.S. Geological Survey Professional Paper 1286, pubs.er.usgs.gov/usgspubs/pp/pp1286

Winston, M.R., Taylor, T.M., and Pigg, J., 1991, Upstream extirpation of four minnow species due to damming of a prairie stream: Transactions of the American Fisheries Society, v. 120, p. 98–105.

Wohl, E., 2004, Disconnected rivers—linking rivers to landscapes: New Haven, Connecticut, Yale University Press.

Wohl, E., Angermeier, P., Bledsoe, B., Kondolf, G., MacDonnell, L., Merritt, D., Palmer, M., Poff, N., and Tarboton, D., 2005, River restoration: Water Resources Research, v. 41, W10301.

Wolman, M.G., and Gerson, R., 1978, Relative scales of effectiveness of climate in watershed geomorphology: Earth Surface Processes, v. 3, p. 189–208.

Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphic processes: Journal of Geology, v. 68, p. 54–74.

Wootton, R.J., 1990, Ecology of teleost fishes: London, Chapman and Hall.

Wurbs, R.A., Hoffpauir, R.J., Olmos, H.E., and Salazar, A.A., 2005, Conditional reliability, sub-monthly time step, flood control, and salinity features of WRAP: College Station, Texas, Texas Water Resources Institute Draft Technical Report TR-284, twri.tamu.edu/reports/2005/tr284.pdf

15 *Appendix*

15.1
ACRONYMS/SYMBOLS

7Q2	Seven-Day Two-Year Low Flow
D_{50}	Median particle diameter
ETM+	Enhanced Thematic Mapper Plus
GIS	Geographic Information System
GPS	Global Positioning System
Q	Discharge
QS	Sediment discharge (bed load portion)

15.2
GLOSSARY OF SELECTED TERMS

303(d) list: statewide list of water bodies that are not meeting water quality standards set for their use. The list is produced by the Texas Commission on Environmental Quality every two years and submitted to the U.S. Environmental Protection Agency.

7Q2: see **seven-day two-year low flow**

abiotic: any non-biological feature or process, such as geological or meteorological characteristics.

acre-foot: the volume of water needed to cover 1 acre to a depth of 1 foot. It equals 325,851 gallons or 43,560 cubic feet.

active floodplain: area of a floodplain periodically covered by floods during current hydrologic and geomorphic conditions, as opposed to terraces, which are areas of the historic floodplain that are seldom or never covered by floods during current conditions.

adaptive management: a process for implementing policy decisions as an ongoing activity that requires monitoring and adjustment. Adaptive management applies scientific principles and methods to improve resource management incrementally as managers learn from experience and as new scientific findings and social changes demand.

aggradation: a progressive build up of the channel bed with sediment over several years, distinguished from the rise and fall of the channel bed during a single flood, which is due to a normal sequence of scour and deposition.

anabranch: a secondary channel of a stream which leaves and then rejoins the main channel. The two channels are separated by stable, vegetated islands.

aquatic life use: a beneficial use designation in which the water body provides suitable habitat for survival and reproduction of desirable fish, shellfish, and other aquatic organisms.

armoring: the formation of an erosion-resistant layer of relatively large particles on a streambed or bank resulting from removal of finer particles by erosion.

assemblage: an organism group of interacting species in a given ecosystem, for example, a fish assemblage or a benthic macroinvertebrate assemblage.

assimilative capacity: the ability of a natural body of water to degrade and/or disperse chemical substances without adverse effects. If the rate of introduction of pollutants into the environment exceeds its assimilative capacity, habitat and wildlife may be adversely affected.

attenuation: the process whereby the magnitude of a flood event is reduced by slowing, modifying, or diverting the flow of water.

bank: the sloping land bordering a channel that forms the usual (not the flood) boundaries of a channel. The bank has a steeper slope than the bottom of the channel and is usually steeper than the land surrounding the channel. Right and left banks are named facing downstream (in the direction of flow).

bank stability: occurs when the channel bank configuration does not change significantly over time. Examples of bank instability include channel widening or narrowing and large changes in the meander migration rate.

base flows: the component of an instream flow regime that represents normal flow conditions (including variability) between precipitation events. Base flows provide a range of suitable habitat conditions that support the natural biological community of a specific river sub-basin.

bathymetric: related to the measurement of water depth within a water body.

bed forms: three-dimensional configurations of bed material, which are formed in streambeds by the action of flowing water.

bed load: sediment that is transported by a stream on or very close to the bed.

bed stability: occurs when the average elevation of the streambed does not change significantly over time. Aggradation and degradation are the two forms of bed instability.

benthic: pertaining to the bottom of a body of water, on or within the bottom substrate material.

biodiversity: the variety of plant, animal, and microorganism species present in the ecosystem and the community structures they form.

biogeochemical cycling: the flow of chemical substances to and from the major environmental reservoirs: Atmosphere, Hydrosphere, Lithosphere, and Biosphere.

biota: the plant (flora) and animal life (fauna) of a region or ecosystem.

boundary conditions: definition or statement of conditions or phenomena at the boundaries of a model; water levels, flows, and concentrations that are specified at the boundaries of the area being modeled.

calibration: to check, adjust, or determine by comparison that a computer model will produce results that meet or exceed some defined criteria within a specified degree of confidence.

canopy: the overhanging cover formed by branches and foliage.

channel: a natural or artificial watercourse that continuously or intermittently contains water, with definite bed and banks that confine all but overbanking streamflows.

Chezy's equation: an empirical equation used to estimate the average hydraulic conditions of flow within a channel cross section. Alternative to Manning's equation.

Chezy's roughness: a coefficient in Chezy's equation that accounts for energy loss due to the friction between the channel and the water.

Clean Rivers Program: see Texas Clean Rivers Program

Clean Water Act: see federal Clean Water Act

connectivity: refers to the movement and exchange of water, nutrients, sediments, organic matter, and organisms within the riverine ecosystem. Connectivity occurs laterally (between the stream and its floodplain), longitudinally (along the stream), vertically (between the stream and groundwater), and temporally.

control variables: large-scale environmental factors that control patterns found in local geomorphic features. Examples include geology, soils, land use, hydrology, planform channel features, and valley characteristics.

cover (instream cover): overhanging or instream structure, such as tree roots, undercut streambanks, boulders, or aquatic vegetation that offer protection for aquatic organisms.

current velocity: the velocity of water flow in a stream, measured in units of length per time such as feet per second (ft/s or fps) or meters per second (m/s).

cutoff: where the stream cuts through the neck of a meander bend.

detritus: decaying organic matter (predominantly leaves and other matter from vegetation).

Digital Elevation Model: a representation of a topographic surface arranged in a data file as a set of regularly spaced x, y, z coordinates where z represents elevation.

Digital Orthographic Quarter Quadrangle: a digital aerial photography data set that has been processed to correspond to U.S. Geological Survey 1:12,000-scale quarter-quadrangle topographic maps.

Discharge (Q): the volume of water passing a point per unit time.

ecoregion: a geographic area over which the macroclimate is sufficiently uniform to permit development of similar ecosystems on sites with similar geophysical properties. Ecoregions contain multiple landscapes with different spatial patterns of ecosystems.

ecosystem: an assemblage of living organisms interacting with physical and chemical features as an environmental unit.

ecotone: a transition zone between two distinctly different ecosystems or communities.

eddy viscosity: a model parameter that reproduces the effects of turbulent mixing in fluid flow.

electrofishing: a biological collection method that uses electric current to facilitate capturing fishes.

embeddedness: a measure of the degree that gravel and larger substrates are surrounded by fine particles (silt and sand).

endemism: the characteristic of being confined to or indigenous in, a certain area or region.

federal Clean Water Act: more formally referred to as the Federal Water Pollution Control Act, the Clean Water Act constitutes the basic federal water pollution control statute for the United States.

finite difference: a method of solving the governing equations of a numerical model by dividing the spatial domain into a mesh of nodes. Solution of the governing equations is approximated from values at the node locations.

finite element: a method of solving the governing equations of a numerical model by dividing the spatial domain into elements in each of which the solution of the governing equations is approximated by a continuous function.

finite volume: a method of solving the governing equations of a numerical model by dividing the spatial domain into a mesh of nodes and corresponding volumes around each node. Solution of the governing equations is obtained from approximations of the fluxes across the boundaries of adjacent volumes.

flashiness: a measure of a river or stream's tendency to carry a high percentage of its flow volume in large, infrequent events rather than more moderate flows that occur frequently.

flood: a flow that exceeds the normal channel capacity and goes over the banks of a stream or river.

flood frequency: how often, on average, a discharge of a given magnitude occurs at a particular location on a stream. Usually expressed as the probability that the discharge will exceed some size in a single year (the 1-in-100 year flood has a 1 percent probability of being equaled or exceeded in any one year).

floodplain: a relatively flat area adjacent to a stream that is periodically inundated.

flow duration curve: a measure of the range and variability of a stream's flow. The flow duration curve represents the percent of time during which specified flow rates are exceeded at a given location. This is usually presented as a graph of flow rate (discharge) versus percent of time that flows are greater than, or equal to, that flow.

flow-sensitive habitats: habitats that show hydraulic response to relatively small changes in streamflow; responses may be reflected in changes in depth, velocity patterns, wetted width and/or habitat area; may be substantially affected by reductions in stream flows. Examples include shallow-water, edge, and riffle habitat.

food web: a model structure used to represent the links between organisms within an environment, based upon the order in which various organisms consume one another.

freshwater inflow requirements: freshwater flows required to maintain the natural salinity, nutrient, and sediment delivery in a bay or estuary that supports their unique biological communities and ensures a healthy ecosystem.

Froude number: ratio of the inertial to gravitational forces within a fluid. Froude numbers greater than 1 correspond to super-critical flow, less than 1 to subcritical flow.

guild: a group of species or organisms that use the same environmental resources (habitat, food source, etc.) or life history strategy (e.g., reproduction) in the same way.

habitat: the native environment or specific surroundings where a plant or animal naturally grows or lives. Habitat includes physical factors such as temperature, moisture, and light together with biological factors such as the presence of food or predator organisms.

hardwood bottomland: hardwood forested lowlands adjacent to some rivers, especially valuable for wildlife breeding, nesting, and habitat.

high flow pulses: the component of an instream flow regime that represents short-duration, in-channel, high flow events following storm events. They maintain important physical habitat features and longitudinal connectivity along the river channel.

hydraulic control: a feature in a stream (such as a constriction or weir) that controls the upstream water surface elevation.

hydraulic model: a computer model of a segment of river used to evaluate hydraulic conditions.

hydraulic roughness: an estimate of the resistance to flow due to energy loss caused by friction between the channel and the water. Chezy's and Manning's roughness are two different ways to express this parameter.

hydrograph: graph showing the variation of water elevation, velocity, streamflow, or other property of water at a particular location with respect to time.

hydrologic model: a computer model of a watershed used to evaluate how precipitation contributes to flow in streams (rainfall/runoff analysis).

hyporheic zone: the zone under a river or stream comprising substrate whose interstices are filled with water.

impaired water body: a water body that cannot reasonably be expected to attain or maintain applicable water quality standards, and at least one beneficial use shows some degree of degradation.

imperiled species: declining, rare, or uncommon species; species federally listed as threatened or endangered, or candidates for such; and species with limited distributions.

Index of Biotic Integrity: a multi-metric measure of biological condition developed from collection data for fish or other organisms. It consists of metrics in three broad categories: species composition, trophic composition, and organism abundance and condition.

instream flow recommendation: the instream flow conditions (i.e., the magnitude and timing of flow events) necessary to maintain an ecologically sound environment in rivers and streams as developed by applying the best available methods. Recommendations are in the form of an instream flow regime that includes subsistence flows, base flows, high flow pulses, and overbank flows.

interstitial spaces: gaps between the particles that make up the streambed.

key habitats: flow-sensitive habitats as well as habitats that support key species.

key species: species that are targeted for instream flow assessment or more generally taxa of interest; may include lotic-adapted species, imperiled species, sport fishes, or other species related to study objectives.

lotic: relating to moving water such as streams and rivers.

lotic-adapted species: species for which all or part of their life history is dependent on flowing water. Examples of lotic-adapted species are riffle-dwelling fishes such as darters, blue sucker, riverine mussels, aquatic invertebrates, and others.

macroinvertebrate: an animal without a backbone, large enough to be seen without magnification and unable to pass through 0.595 mm mesh.

macrophyte: macroscopic plants in the aquatic environment. The most common macrophytes are the rooted vascular plants that are usually arranged in zones in aquatic ecosystems and restricted in their area by the extent of illumination through the water and sediment deposition along the shoreline.

Manning's equation: an empirical equation used to estimate the average hydraulic conditions of flow within a channel cross section.

Manning's roughness: a coefficient in Manning's equation that accounts for energy loss due to the friction between the channel and the water. Many hydraulic models use this coefficient to estimate resistance to flow.

mean column velocity: the average velocity of fluid flow measured in a column extending from the surface of the water to the bed of the channel. Often referred to simply as "velocity" or "current velocity." In contrast, point velocity is measured at a single point in the water column.

median particle size (D_{50}): value for which half the particles in a sample have a greater diameter and half a lesser diameter.

mesohabitat: basic structural elements of a river or stream such as pools, backwaters, runs/glides, and riffles.

microhabitat: zones of similar physical characteristics within a mesohabitat unit, differentiated by aspects such as substrate type, water velocity, and water depth.

modified Wentworth scale: a specific scale used to classify substrate particles by their diameter. Categories in this scale include boulder, cobble, pebble, gravel, sand, silt, and clay.

National Elevation Dataset: a Digital Elevation Map developed and maintained by the U.S. Geological Survey that provides the best available elevation data for the conterminous area of the United States.

naturalized conditions: an estimate of natural conditions obtained by attempting to remove effects of human activities from a set of measured conditions.

Navier-Stokes equations: a set of equations that describe the physics governing the motion of a fluid. In addition to applications in hydraulic studies of rivers and streams, these equations are used to model weather, ocean currents, and aerodynamics.

nutrient cycle: the cyclic conversions of nutrients from one form to another within biological communities. A simple example is the production and release of molecular oxygen from water during photosynthesis by plants and the subsequent reduction of atmospheric oxygen to water by the respiratory metabolism of other biota.

overbank flows: the component of an instream flow regime that represents infrequent, high flow events that exceed the normal channel. These flows maintain riparian areas and provide lateral connectivity between the river channel and active floodplain. They may also provide life-cycle cues for various species.

Peclet number: the relationship between properties of the mesh, fluid velocity, and eddy viscosity for a hydraulic computer model.

physiographic province: an area with similar characteristics based on geology, soil type, and topography.

point velocity: the velocity of fluid flow measured at a single point within a volume of flowing water.

rating curve: a graph showing the relationship between water surface elevation and discharge of a stream or river at a given location. Also called a stage-discharge curve.

reach: in general, a length of stream with relatively homogenous characteristics. In terms of the Texas Instream Flow Program, a subdivision of a segment that exhibits relatively homogeneous channel and floodplain conditions (hydrologic/hydraulic, biological, geomorphic, and water quality).

recruitment: survival of young plants and animals from birth to a life stage less vulnerable to environmental change.

resilience (ecosystem): the ability of an ecosystem to maintain or restore biodiversity, biotic integrity, and ecological structure and processes following disturbance.

response variables: environmental features of the river channel on a local or site-specific scale. Examples include channel shape, cross-sectional dimensions, substrate, bank shape, floodplain characteristics, vegetation, and channel patterns.

return flow: the portion of a diverted flow that is not consumptively used and returns to its original source or another body of water.

riparian area: a zone of transition between aquatic and terrestrial ecosystems that exhibits, through the zone's existing or potential soil-vegetation complex, the influence of surface or subsurface water.

River Styles (RS): a framework for conducting geomorphic analysis of river systems.

river (or riverine) ecosystem: the biotic and abiotic components within the main channel and adjoining floodplain and riparian area of a river segment, their structural relationships, and the processes that maintain them.

routing parameters: coefficients that, along with mathematical routing equations, can be used to estimate the attenuation and lag (time delay) associated with the movement of flow through a length of stream channel.

runoff: rainwater or snowmelt that is transported to streams by overland flow, drains, or ground water.

scour: the erosive action of running water in streams, which excavates and carries away material from the bed and banks.

Or, pertaining to a place on a streambed swept (scoured) by running water.

Section 404: the section of the federal Clean Water Act delineating restrictions on the dredging and filling of wetlands and disruption of beds and banks of streams.

sediment trapping efficiency (E): the ratio of sediment retained within the reservoir to the sediment inflow to the reservoir.

segment: a water body or portion of a water body that is individually defined and classified in the Texas Surface Water Quality Standards. A segment is intended to have relatively homogeneous chemical, physical, and hydrological characteristics.

seven-day two-year low flow (7Q2): the lowest average streamflow for seven consecutive days with a recurrence interval of two years, as statistically determined from historical data. Some water quality standards do not apply at streamflows that are less than the 7Q2 flow.

shear stress: the frictional force per unit area exerted on the streambed by flowing water. An important factor in the movement of bed material and description of habitat for some organisms.

sinuosity: a measure of meander "intensity." The ratio of the length of a stream measured along its thalweg to the length of the valley through which the stream flows.

sound ecological environment: a functioning ecosystem characterized by intact, natural processes, resilience, and a balanced, integrated, and adaptive community of organisms comparable to that of the natural habitat of a region.

species richness: the number of species in an assemblage or sample.

stage: see **water surface elevation**.

stream power: a measure of energy available to move sediment, or any other particle in a stream channel. It is affected by discharge and slope.

sub-basin: in general, a portion of a river basin. In relation to the Texas Instream Flow Program, the full geographic scope of priority studies within major river basins, including the main channel, floodplain, tributaries, and contributing watershed area of all study segments.

sub-critical flow: flow characterized by low velocity and a Froude number less than 1.

subsistence flows: the component of an instream flow regime that represents infrequent, naturally occurring low flow events that occur for a seasonal period of time. They maintain water quality criteria and provide sufficient habitat to ensure organism populations capable of recolonizing the river system once normal, base flows return.

super-critical flow: flow characterized by high velocity and a Froude number greater than 1.

sustainability: the long-term capacity of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity.

taxa: groups of organisms or ecosystems categorized by common characteristics.

Texas Clean Rivers Program: a program administered by the Texas Commission on Environmental Quality which conducts water quality monitoring, assessment, and public outreach activities in the state. Local river authorities are primary partners in this program.

thalweg: a line following the deepest part of the bed of a channel.

time series: a set of data collected sequentially, usually at fixed intervals of time. For example, a hydrologic time series may provide average daily flow values at a particular location for a number of years of observation. A habitat time series could provide an estimate of corresponding average daily habitat conditions for the same time period.

Total Dissolved Solids: a water quality parameter that measures the solids (usually mineral salts) dissolved in water.

Total Maximum Daily Load: the maximum quantity of a particular water pollutant that can be discharged into a body of water without violating a water quality standard.

transport capacity: the capacity of a river to carry sediment in suspension or to move sediment along the riverbed.

trophic structure: the feeding relationships among species within a food web/chain or a single ecosystem.

validation: comparison of computer model results with a set of data that were not used for calibration.

water availability model: a numerical surface water flow model used to determine the availability of surface water for water right permitting in the state.

watershed: the area enclosed by a topographic divide, which drains to a specific location on a stream or river.

water surface elevation (or stage): the elevation of a water surface above or below an established reference level, such as sea level.

water quality: the chemical, physical, biological, radiological, and thermal condition of water.

water quality criteria: a specific level or range of levels of water quality expected to render a body of water suitable for its designated use. Criteria are set for individual pollutants based on different water uses, such as public water supply, aquatic habitat, industrial supply, or recreation.

water quality standards: state-adopted and U.S. Environmental Protection Agency-approved ambient standards for water bodies. Standards include the use of the water body and the water quality criteria that must be met to protect the designated use or uses.

water table: the surface below which soil is saturated with water. Its depth below the ground surface is influenced by rainfall and human development (wells, drainage ditches, loss of wetlands, etc.). Typically, the depth below the surface to the upper layer of groundwater.

wetland: An area (including a swamp, marsh, bog, prairie pothole, or similar area) having a predominance of hydric soils that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support and that under normal circumstances supports the growth and regeneration of hydrophytic vegetation. The term “hydric soil” means soil that, in its undrained condition, is saturated, flooded, or ponded long enough during a growing season to develop an anaerobic condition that supports the growth and regeneration of hydrophytic vegetation. (“Hydrophytic vegetation” is a plant growing in water or a substrate, which is at least periodically deficient in oxygen during a growing season as a result of excessive water content.)

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