TEXAS INSTREAM FLOW STUDIES: TECHNICAL OVERVIEW

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Executive Summary

Senate Bill 2 established the Texas Instream Flow Program (TIFP), which is jointly administered by the Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board. The purpose of the TIFP is to perform scientific and engineering studies to determine flow conditions necessary to support a sound ecological environment in the river basins of Texas.. TIFP instream flow studies for river sub-basins will be conducted as shown in Figure ES-1.

Activities listed above the horizontal line in Figure ES-1 are components of the Senate Bill 2 authorization for the TIFP. Activities completed during these steps are described in more detail in Tables ES-1 through ES-4 and throughout this document.

The goal of TIFP studies is to determine flow conditions necessary to support a sound ecological environment for specific river sub-basins in Texas. To accomplish this goal, 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 meeting this goal. Study-specific goals and objectives consistent with the definition of a sound ecological environment will be determined in consultation with stakeholders. These definitions will be compatible with all applicable state and federal laws, as well as statewide TIFP goals.

The geographic vastness of the State 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 TIFP 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 ES-2 through ES-5. Flow components will be identified for wet, normal, and dry hydrologic conditions, as appropriate.

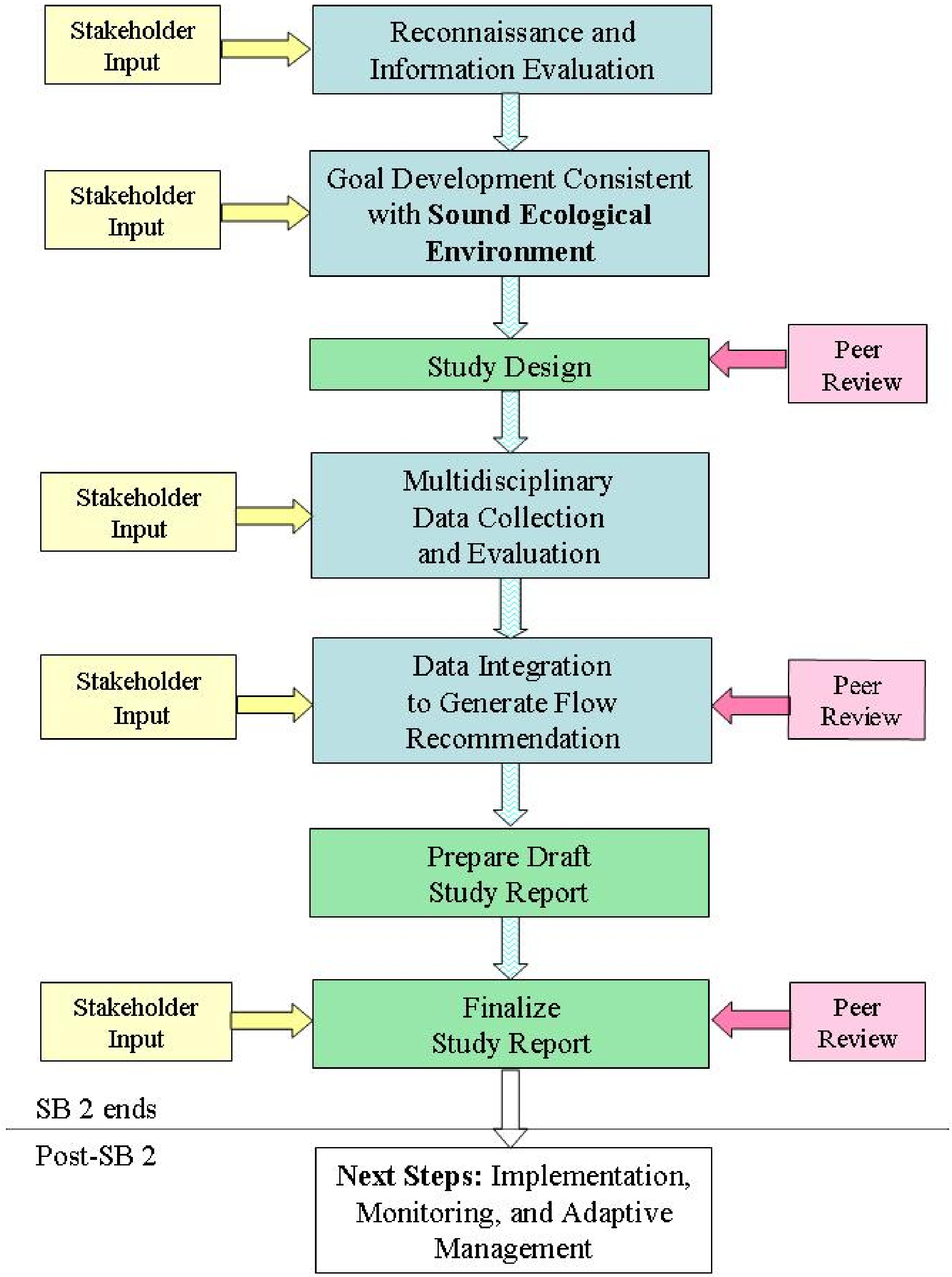

Figure ES-1. Steps in sub-basin studies of the Texas Instream Flow Program (TIFP).

Table ES-1. TIFP sub-basin activities summary - Step 1: Reconnaissance & Information Evaluation.

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

- USGS and other gauge data.
- Past federal/state/local studies.
- Historic air photos/DOQ/maps/soil surveys.
- Current WQ models and standards.

Activities

Hydrology and Hydraulics

- Calculate historic and current flow statistics.
- Identify existing features (e.g. tributaries) and existing and proposed alterations (diversions, impoundments, land uses, etc) affecting hydrologic character.

Biology

- Identify 1) historic, current, threatened, endangered, and key species present, 2) representative and key habitat types, and 3) biological issues and considerations.
- Assess historic and current condition of stream biota and riparian resources.
- Identify potential study reaches and sites.

Geomorphology

- Analysis of aerial photography and other historic data as available.
- Assess 1) channel bedform and banks, 2) active channel and floodplain processes, and 3) 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.
- Develop conceptual models to describe the relationships between ecological health and flow regime.
- Prioritized list of research needs to address identified knowledge gaps.

Scale: All Scales

Table ES-2. TIFP sub-basin activities summary - Step 2: Goal Development & Study Design.

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 1) intensive study sites, 2) specific technical tools and sampling criteria, and 3) 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

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 TIFP Technical Overview.

Scale: All Scales

Table ES-3. Summary of TIFP sub-basin activities during Step 3: Multidisciplinary Data Collection and Evaluation.

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

Hydrology and Hydraulics

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

Biology

- Collect biological data including species, count, life stage, flow, depth, velocity, substrate, and channel location.
- 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 ES-4. Summary of TIFP sub-basin activities during Step 4: Data Integration to Generate Flow Recommendations.

Step 4: Data Integration to Generate Flow Recommendations

Purpose

- Construct instream flow regime (including subsistence, base, high pulse, and overbank flows) 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

Hydrology and Hydraulics

- Calculate occurrence of various flow rates during historical and current conditions.
- Determine annual variability of hydrologic characteristics, including description of wet, normal and dry years.
- 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 monthly flow ranges for key species and 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 recommended flow regime, ecological significance of flow components, and study methods and analysis.

Scale: River Segment

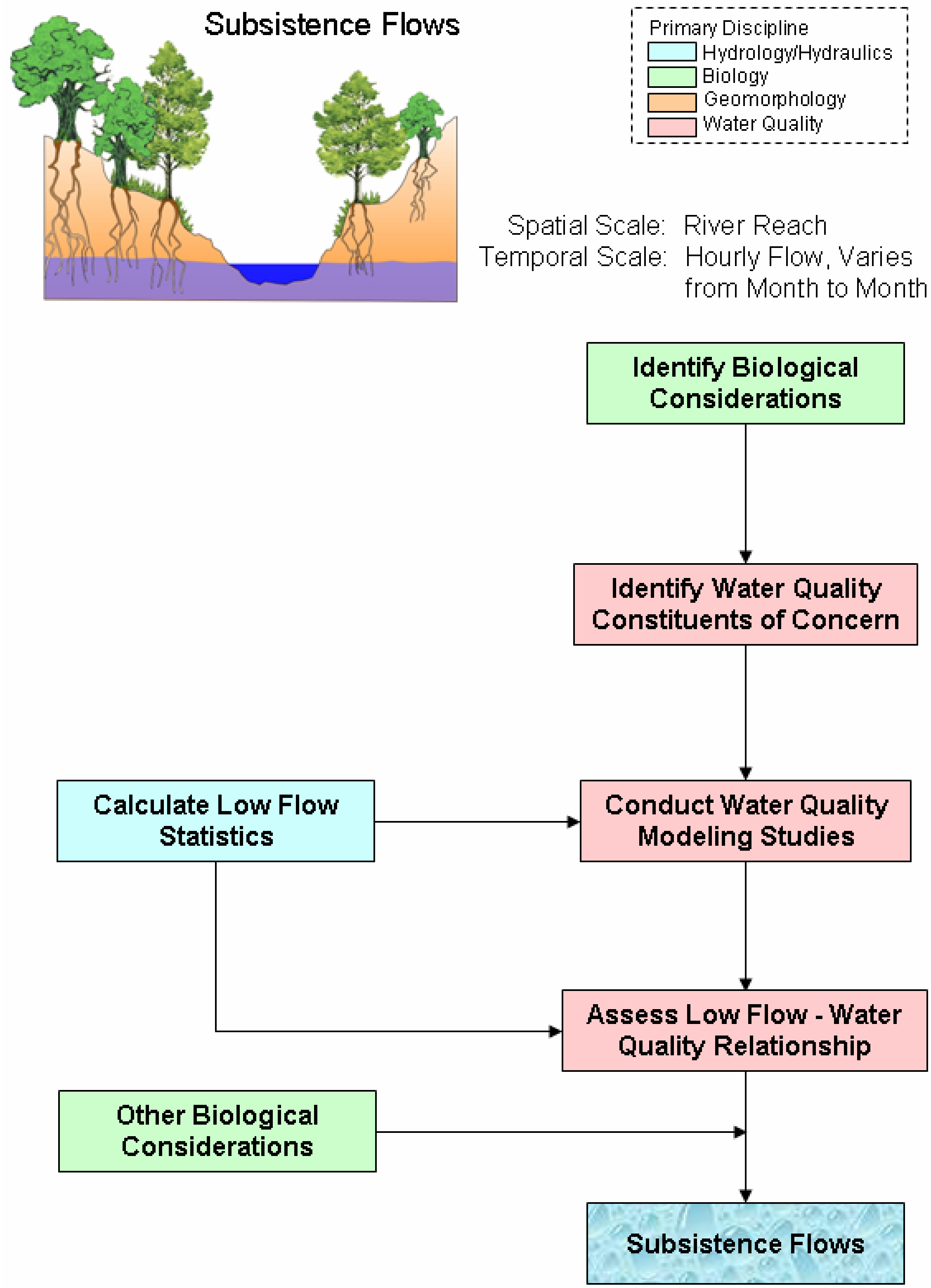

Figure ES-2. Development of subsistence flows from results of multidisciplinary activities.

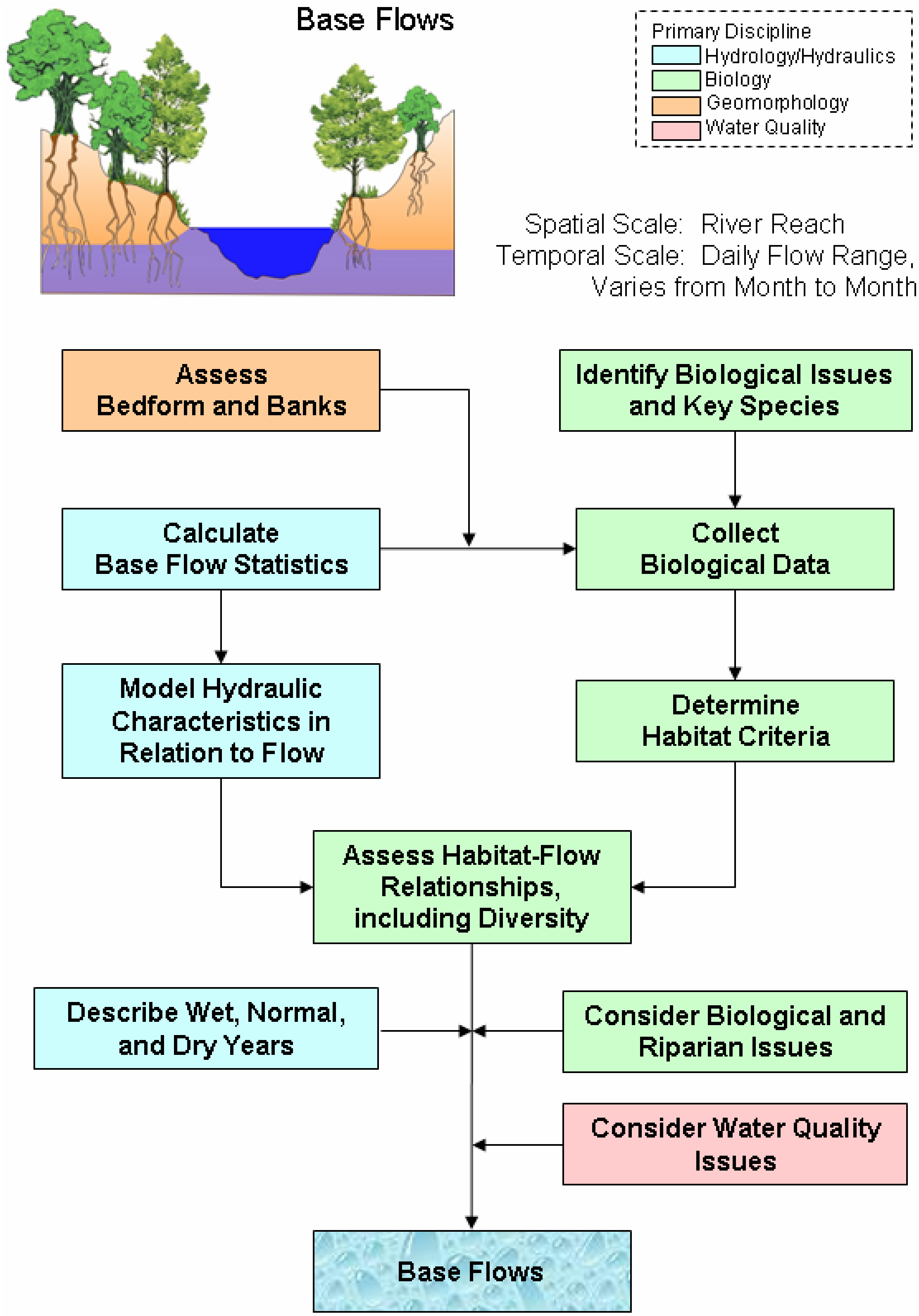

Figure ES-3. Development of base flows from results of multidisciplinary activities.

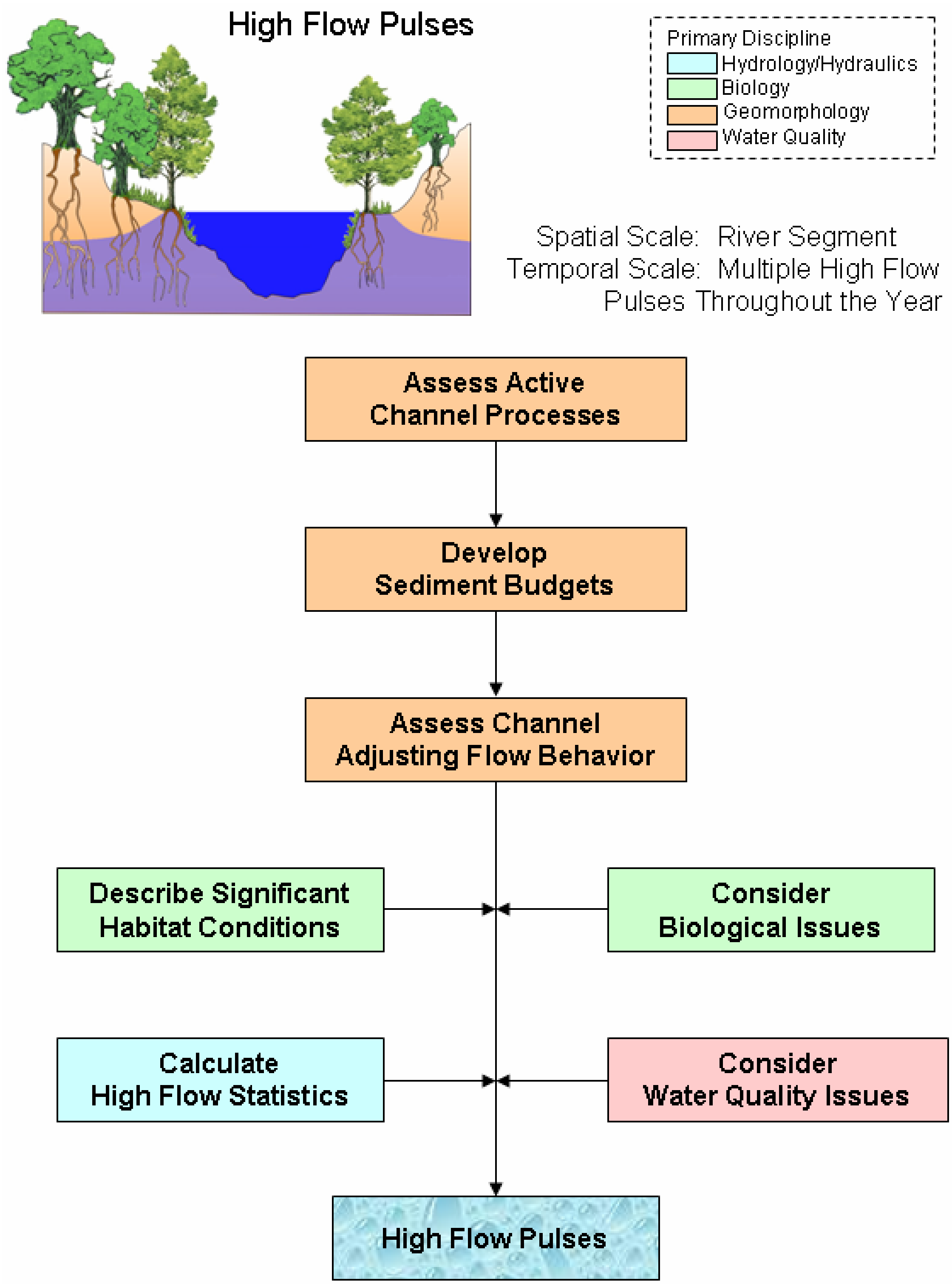

Figure ES-4. Development of high flow pulses from results of multidisciplinary activities.

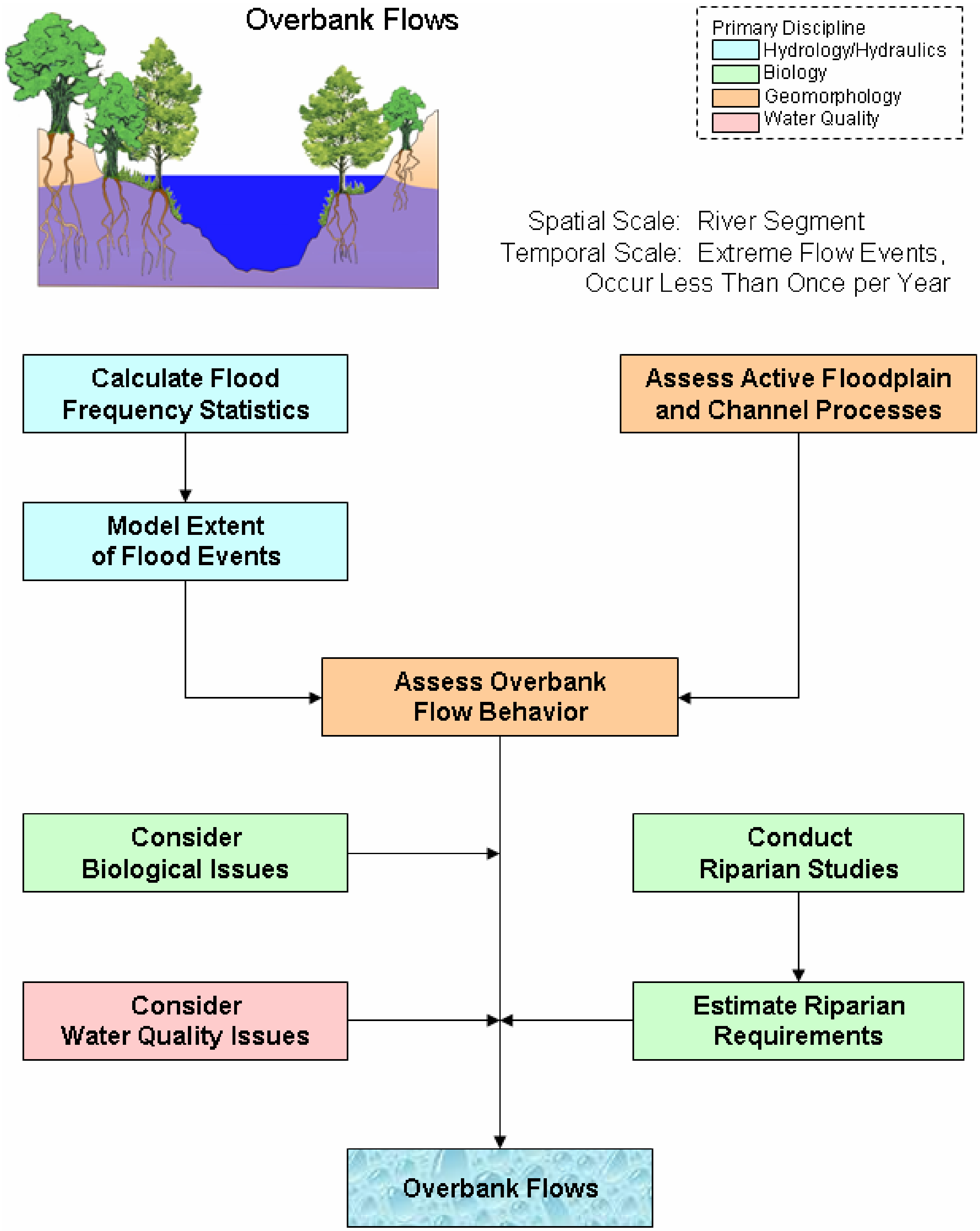

Figure ES-5. Development of overbank flows from results of multidisciplinary activities.

1. Introduction

In 2001, the Texas Legislature enacted Senate Bill 2 establishing the Texas Instream Flow Program (TIFP) that is being cooperatively developed and jointly administered by the Texas Commission on Environmental Quality (TCEQ), Texas Parks and Wildlife Department (TPWD), and Texas Water Development Board (TWDB) (hereafter referred to as “the Agencies”). The purpose of the TIFP is to perform scientific and engineering studies to determine flow conditions necessary to support a sound ecological environment in the river basins of Texas.

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 40 million in 2050 with attendant shortages of water (TWDB, 2002). If the State does not ensure sufficient water to meet projected needs, socioeconomic models predict reduced economic growth and vitality (TWDB, 2002). Additionally, the impact on hunting and fishing could be tremendous. Sansom (1995) states:

> “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 (CITE). 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 is intimately linked to instream flows. Rivers, streams and riparian areas cumulatively assimilate large volumes of nutrients and organic materials from both natural and anthropogenic sources, such as wastewater and non-point source runoff. Rivers and streams and their associated riparian areas support a tremendous diversity of plants and animals, several of which are known to occur exclusively in Texas.

1.1 History of Texas Instream Flow Program

The 77th session of the Texas Legislature passed Senate Bill 2 in 2001, directing the TCEQ, TPWD, and TWDB to "…jointly establish and continuously maintain an instream flow data collection and evaluation program…" In addition, the Agencies were directed to "…conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state rivers and streams necessary to support a sound ecological environment." The TIFP was developed by the Agencies in response to this directive.

The Agencies signed a Memorandum of Agreement (MOA) in October 2002. The MOA provides 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. A Programmatic Work Plan (PWP) for TIFP studies was completed by the Agencies in December 2002. The PWP identifies priority studies and interim deadlines for publications, outlines the roles of the state agencies, and presents the scope of the studies and general methods that will be used to conduct the studies. A draft Texas Instream Flow Studies: Technical Overview (TO) was completed in August 2003. The draft Technical Overview provided an in-depth discussion of the instream flow methods proposed for use by the TIFP.

In June of 2003, the PWP and draft Technical Overview were submitted to the National Research Council (NRC) of the National Academy of Sciences (NAS) as part of a scientific peer review of the TIFP. This review was completed in February 2005 and results are documented in report format (NRC, 2005). The Agencies have revised the Technical Overview in response to recommendations of the National Research Council. After completion of internal review within the Agencies, the Technical Overview will be submitted for stakeholder evaluation starting in May 2006.

The Agencies maintain a website (http://www.twdb.state.tx.us/instreamflows/index.html) where documents and information related to the TIFP can be accessed.

1.2 Texas Instream Flow Program Approach to Sub-basin Studies

The TIFP will conduct basin-specific studies in selected sub-basins with an ecosystem focus. These studies will also be subject to scientific realities and reflect a larger programmatic context (Table 1.1). The TIFP 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 project goals. The TIFP 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. Procedures and methods employed in the TIFP will need to adapt and change over time as scientific understanding of the issues surrounding instream flow studies deepens. In order to fit within its program context, the TIFP will be transparent to the public, involve stakeholders and scientific peers, and strive for compatibility with existing programs.

Table 1.1. Approach and underlying principles of the Texas Instream Flow Program.

Approach/Principles
Ecosystem Focus • Studies need to be **multidisciplinary**, **multi-scale**, and **focused on processes**. • Recommendations will specify a **flow regime**.
Scientific Realities • Instream flows have an **important but not exclusive role** in supporting ecosystems. • Study results will incorporate **uncertainty**. • Procedures and methods will need to **adapt and change**.
Program Context • Studies need to be **transparent** to the public. • Studies need to **involve stakeholders and scientific peers**. • TIFP needs to be **compatible** with existing state and federal programs.

1.2.1 Ecosystem Focus

Senate Bill 2 gives the TIFP 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 1.2. 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 TIFP that focuses on entire riverine ecosystems. The goal of ensuring a "sound ecological environment" has been equated to maintaining the ecological integrity and conserving the biological diversity of riverine ecosystems. In order to meet these goals, the Agencies recognize the importance of maintaining the natural habitat diversity, hydrologic character, and water quality of river systems.

Text Box 1.1. Definition of terms related to Texas Instream Flow Program goals.

A **sound ecological environment** is 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.

A **riverine ecosystem** is the biotic and abiotic (non-living) components within the main channel and adjoining floodplain and riparian area of a river segment, their structural relationships, and the processes that maintain them.

Ecological integrity is analogous to "health" of a riverine ecosystem (Adamus, 1996; NRBSB, 1996; Whitington et al., 2001). It is achieved when a river ecosystem has all its parts structured and functioning in a "natural" way, can continue to maintain itself in this form within the natural disturbance regime, and all processes are taking place at normal rates.

Biodiversity is the variety of plant, animal and microorganism species naturally present in the ecosystem and the community structures they form.

Habitat diversity is the variety of physical habitats found within the river system.

Hydrologic character is the natural flow behavior of the river, including variation in the magnitude and timing of peak, minimum, and other flows. It includes variation throughout the day and from day to day, season to season, and year to year.

Normal or **natural** conditions can be defined by long term monitoring of a river segment or comparison to "reference" river segments. Reference segments may be chosen to represent un-impacted, least-impacted, or representative conditions.

Table 1.2. Environmental considerations related to streams/rivers as directed by state statutes.

Consideration	Statute
will not cause … adverse impact on … the environment of the stream	TAC 297.45(b)
no adverse impact to … the environment	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	TAC 297.53(a)
mitigate adverse impacts, if any, on fish and wildlife habitat	TAC 297.53(b)
assessment … shall include the project site as well as potentially impacted habitat upstream, adjoining, and downstream	TAC 297.53(c)
… "no net loss" of wetland functions and values. 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.	TAC 297.53(e)
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	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	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

Multidisciplinary

The ecosystem focus of TIFP studies requires a multidisciplinary approach. Because of their complexity, it is widely accepted that studies of riverine ecosystems should be multidisciplinary (see, for example, Palmer et al., 2003; Wohl et al., 2005). Components related to hydrology, geomorphology, biology, water quality, and connectivity must be considered in order to adequately address flow needs of aquatic ecosystems (Annear et al., 2004). Studies conducted by the TIFP will follow this conceptual model. The Agencies have agreed to explicitly include the disciplines of hydrology, biology, geomorphology, and water quality in their studies and supplement their expertise with outside resources as necessary.

Multi-scale

TIFP studies will require a multi-scale 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 basin-wide 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 for the TIFP that considers a range of spatial and temporal scales.

Processes

An ecosystem approach also requires the TIFP to focus on essential ecological processes. Riverine ecosystems are complex systems of interacting abiotic and biotic components. In order to understand and manage these systems effectively, important processes (e.g., food web dynamics, reproductive cues, species recruitment and colonization) related to the interaction of components must be understood. Attempting to manage a riverine ecosystem without adequate understanding of such processes can be problematic. For example, because essential riverine processes were not understood, many river restoration projects in California have been unnecessary, unsuccessful, or even detrimental (Kondolf, 1998). Understanding the essential processes of a specific river ecosystem may require conducting a number of technical studies.

Flow regime

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 et al. (2004) concluded that such recommendations have not succeeded in adequately maintaining riverine ecosystems. It is now recognized by river scientists that a range of flows are required to maintain healthy riverine ecosystems (e.g., Brown and King, 2003; Schofield et al., 2003). Based on the results of technical studies, the TIFP will identify a set of flow components that support important processes. Example components are shown in Table 1.3. For a specific river sub-basin, additional flow components may be required.

1.2.2 Scientific Realities

While conducting sub-basin studies, the Agencies will maintain an awareness of scientific realities. The Agencies recognize the important, but not exclusive, role that flows play in supporting a “sound ecological environment.” They recognize that knowledge and understanding of riverine ecosystems is imperfect and study results will incorporate uncertainty. The procedures and methods used to develop flow recommendations for Texas rivers will need to adapt and change as understanding of these ecosystems increases.

Table 1.3. Components of an instream flow regime and supported processes (adapted from MEA, 2005; NRC, 2005).

Component	Hydrology	Geomorphology	Biology	Water Quality
Subsistence Flows	Infrequent, low flows	Increased deposition of fine and organic particles	Restricted aquatic habitat Limited connectivity	Elevated temperature and constituent concentrations Reduced levels of dissolved oxygen
Base Flows	Normal flow conditions, including variability	Maintain soil moisture and groundwater table Maintain a diversity of habitats	Suitable aquatic habitat Connectivity along channel corridor	Suitable in-channel water quality
High Flow Pulses	In-channel, short duration, high flows	Maintain channel and substrate characteristics Prevent encroachment of riparian vegetation	Recruitment events for organisms Connectivity to near-channel water bodies	Restore in-channel water quality after prolonged low flow periods
Overbank Flows	Infrequent, high flows that exceed normal channel	Lateral channel movement and floodplain maintenance Recharge floodplain water table New habitat construction Flush organic material into channel Deposit nutrients in floodplain	New life phase cues for organisms Maintain diversity of riparian vegetation Conditions for seedling development Connectivity with floodplain	Restore water quality in floodplain water bodies

Important but not exclusive role

Instream flows play an important part in creating a “sound ecological environment” because almost every process in riverine ecosystems is flow related, As shown in Table 1.4, however, many human activities also affect riverine ecosystems, often adversely. In most cases, implementation of adequate instream flows should provide measurable improvements in ecological integrity. But adequate timing and quantity of instream flows may not be enough to ensure ecosystem goals are met. Instream flow regimes, in and of themselves, are not sufficient to maintain the ecological integrity of a river (e.g. Schofield et al., 2003). The TIFP will identify factors in addition to flow alteration that are affecting study river segments. These additional factors and their ecological effects will be reported and quantified in study results as is practicable given time and budget constraints.

Table 1.4. Human activities adversely affecting riverine ecosystems
(adapted from FISRWG, 1998; Giller, 2005).

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

Uncertainty

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 (e.g., 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 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 would be monitored for goal attainment. If achievement fell short of goals, an adaptive process would be invoked to adjust implementation measures. The exact procedure for implementing instream flow recommendations in Texas remains to be determined, but whatever implementation procedures are adopted, they 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."

Adaptation and change

Through time, the Agencies will adapt and change study procedures and methods as necessary to improve the TIFP. It would seem advantageous for the TIFP to examine all major rivers in Texas with one identical set of methods and procedures suitable for all conditions. This would facilitate comparison of results from one study to the next. However, given the diversity of Texas river systems, one set of tools may not be sufficient. Each basin represents a unique set of features or issues that will dictate variations in the methods and procedures. Additionally, only a few studies have been conducted on the flow requirements of large river systems (Welcomme and Halls, 2004). Established methods and procedures may need to be refined in order to study all of the major rivers of Texas. One example involves regionalized indices of biotic integrity (IBIs). Although regionalized IBIs for wadable streams have recently been developed they have not been adapted for use in large rivers in 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 TIFP studies.

1.2.3 Program Context

The Agencies recognize that the TIFP will function within a broader context that includes political and socio-economic concerns and other government programs related to the management of river ecosystems. The TIFP will be conducted in the public view. Sub-basin goals, objectives, and study designs will be developed with stakeholder input. Peers from the scientific community will provide reviews of study designs and reports. It is expected that the peer review process will increase public confidence in study results and, therefore, the likelihood of implementation of flow recommendations. The Agencies also recognize that many existing state and federal programs whose activities affect, monitor, or regulate rivers within the State of Texas. To the extent possible, the TIFP will coordinate activities in order to maintain consistency with these programs.

Transparency

The Agencies will make every effort to ensure that the activities of the TIFP are transparent to the public. Public documents, such as this one, will describe study approach, methods, and procedures. For all river studies, final study designs, reports, and supporting documents will be available to the public. Candid discussions of uncertainties and limitations associated with methods and procedures will be included in these documents. To promote transparency, the Agencies have developed and continue to maintain a web site documenting TIFP activities (http://www.twdb.state.tx.us/instreamflows/index.html).

Stakeholders and Scientific Peers

In order to ensure public confidence in both the science and values behind instream flow studies, the TIFP will include input from stakeholders and scientific peers. As noted by many (e.g. King et al., 1999; Schofield et al., 2003), instream flow programs require the application of both science and values. To ensure societal values are incorporated, the TIFP will directly involve stakeholders in the development of goals and objectives for sub-basin studies and in all steps of the process described in Figure 1.1, including the finalization of TIFP reports. Scientific peer review is also recognized as an important part of an instream flow assessment program (Arthington et al., 1998; NRC 2005). Overall program documentation of the TIFP and individual study designs and reports will be submitted for scientific peer review. In addition, research findings related to instream flow assessments will be submitted for publication in peer-reviewed journals. This incorporation of scientific peer review will increase the technical soundness of TIFP studies. The combination of stakeholder and scientific peer involvement in the TIFP is expected to increase public trust in instream flow recommendations.

Compatible with existing state and federal programs

The Agencies recognize that the TIFP will be conducted within the broader context of all of the state and federal activities that affect, regulate, or monitor rivers within the State of Texas. The TIFP will make full use of these programs as data sources for evaluating and monitoring river ecosystems. The Agencies 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 on-going programs. For example, water quality investigations will be structured to complement or rely on existing TCEQ water quality programs. The goal will be to build the TIFP 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.

1.3 Layout of Technical Overview

This Technical Overview identifies a process to develop instream flows for major river segments in the State of Texas. This is not a trivial task and there are few models available for guidance. Few programs have attempted to apply procedures to such a diverse range of conditions as found in Texas. Chapter 2 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, yet results must be comparable across the state. 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 the State of Texas. It does 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 1.1. Individual steps in the process are also described in Tables 1.5 through 1.8. Developing instream flow recommendations for specific river segments will be a multidisciplinary effort requiring technical input from numerous fields, including hydrology, biology, geomorphology, and water quality. The process will also incorporate both stakeholder input and peer review.

The first step in the process involves reconnaissance of the specific sub-basins and evaluation of existing information (Table 1.5). 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 effort will be completed with the help of stakeholders, including local river authorities, who are likely to be in possession of or have knowledge of data related to a specific river segment. Existing data and understanding of the river ecosystem will be supplemented by 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 be prioritized. Activities related to this step are discussed in Chapters 3 and 4.

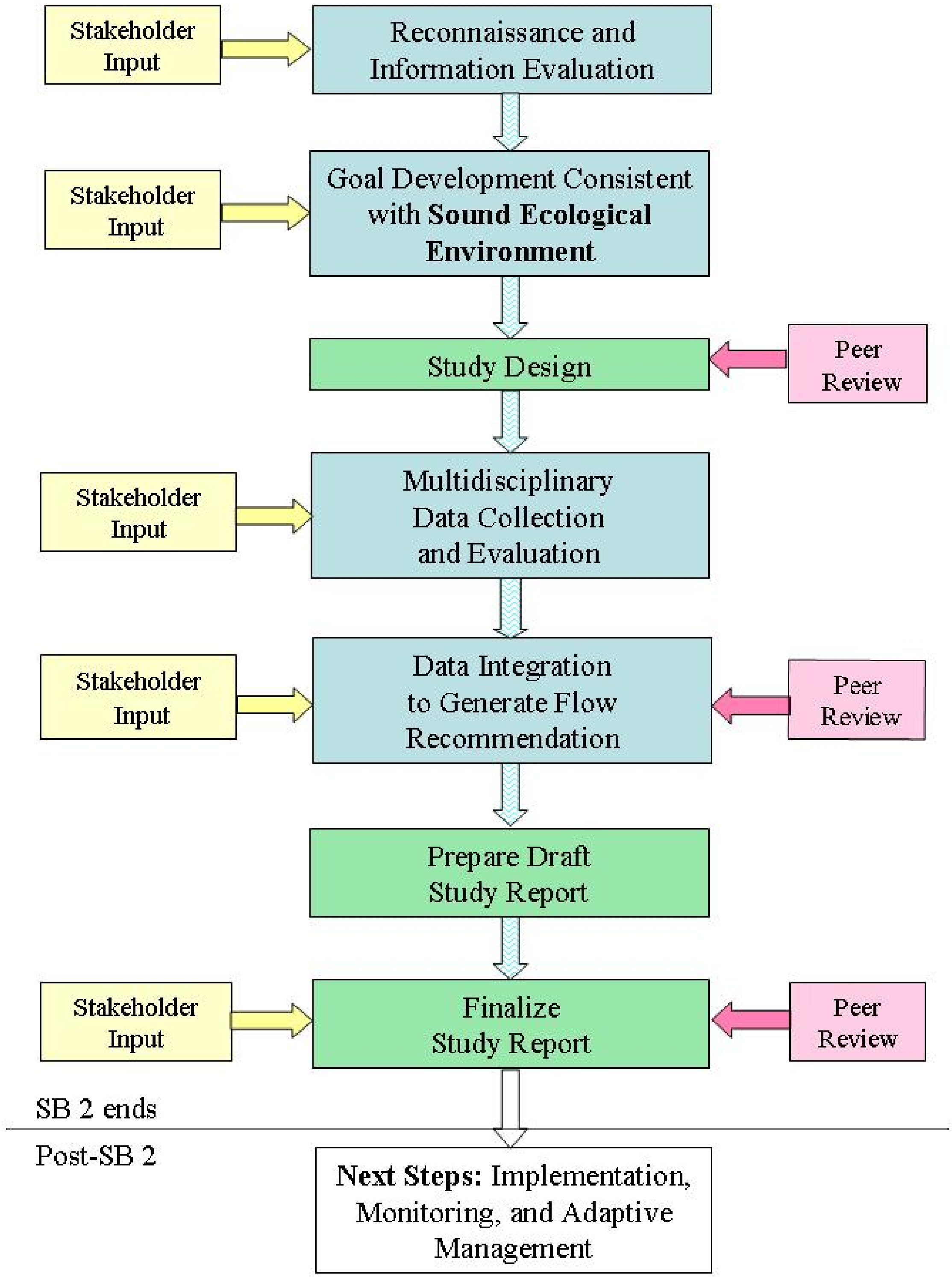

Figure 1.1. River sub-basin specific study steps for the Texas Instream Flow Program (TIFP).

Table 1.5. Summary of TIFP sub-basin study activities during Step 1: Reconnaissance and Information Evaluation.

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

- USGS and other gauge data.
- Past federal/state/local studies.
- Historic air photos/DOQ/maps/soil surveys.
- Current WQ models and standards.

Activities

Hydrology and Hydraulics

- Calculate historic and current flow statistics.
- Identify existing features (e.g. tributaries) and existing and proposed alterations (diversions, impoundments, land uses, etc) affecting hydrologic character.

Biology

- Identify 1) historic, current, threatened, endangered, and key species present, 2) representative and key habitat types, and 3) biological issues and considerations.
- Assess historic and current condition of stream biota and riparian resources.
- Identify potential study reaches and sites.

Geomorphology

- Analysis of aerial photography and other historic data as available.
- Assess 1) channel bedform and banks, 2) active channel and floodplain processes, and 3) 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.
- Develop conceptual models to describe the relationships between ecological health and flow regime.
- Prioritized list of research needs to address identified knowledge gaps.

Scale: All Scales

Table 1.6 Summary of TIFP sub-basin study activities during Step 2: Goal Development and Study Design.

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 1) intensive study sites, 2) specific technical tools and sampling criteria, and 3) 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

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 TIFP Technical Overview.

Scale: All Scales

Table 1.7 Summary of TIFP sub-basin study activities during Step 3: Multidisciplinary Data Collection and Evaluation.

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

Hydrology and Hydraulics

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

Biology

- Collect biological data including species, count, life stage, flow, depth, velocity, substrate, and channel location.
- 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 1.8 Summary of TIFP sub-basin study activities during Step 4: Data Integration to Generate Flow Recommendations.

Step 4: Data Integration to Generate Flow Recommendations

Purpose

- Construct instream flow regime (including subsistence, base, high pulse, and overbank flows) 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

Hydrology and Hydraulics

- Calculate occurrence of various flow rates during historical and current conditions.
- Determine annual variability of hydrologic characteristics, including description of wet, normal and dry years.
- 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 monthly flow ranges for key species and 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 recommended flow regime, ecological significance of flow components, and study methods and analysis.

Scale: River Segment

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 for this step are summarized in Table 1.6 and will be a cooperative effort of the Agencies and stakeholders for the specific sub-basin. 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 future condition of the river. They will also develop goals and objectives for reaching and/or maintaining the desired condition. A set of ecological indicators will be selected to measure progress toward the desired river condition. 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. Potential study sites will be selected and their suitability evaluated. 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 3 and 4.

The third step, described in Table 1.7, is multidisciplinary data collection and evaluation accomplished by technical studies of the river ecosystem. These studies will be conducted by the Agencies and/or their contractors, with input/assistance from stakeholders. Studies will be conducted in accordance with the Study Design agreed upon with stakeholders and finalized after scientific peer review. Efforts of the Agencies will be coordinated to make efficient use of staff, expertise, and resources. Studies will be not only multidisciplinary, but also interdisciplinary in nature. In order 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. When hydrologic and/or seasonal conditions 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 4. The activities of individual disciplines are described in Chapters 5 through 8.

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 1.8. Using the results of technical studies, the Agencies, with stakeholder input, will develop recommendations for an instream flow regime to meet study objectives. This will require the synthesis of study results across several spatial and temporal scales as well as between disciplines. Results will be presented as a range of flows over seasons and years. Ecological consequences of deviations from these targets will be quantified to the greatest extent possible. A study report will include documentation of raw data, collection procedures, methods of analysis, and conclusions. The report 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 3. Procedures to integrate study results and generate flow recommendations are discussed in Chapter 9.

Tables 1.5 through 1.8 represent the extent of TIFP activities authorized by Senate Bill 2. Activities that may occur after development of instream flow recommendations, including implementation, monitoring, and adaptive management, will likely be the product of additional legislative mandates. Implementation of recommendations is arguably the most important step in an instream flow effort. Improvement or protection of a “sound ecological environment” will be a consequence of implementation. If implementation is carried out improperly or not at all, previous steps in the process are rendered ineffectual. Adaptive management is widely recognized as a necessary approach for management of complex ecosystems and is considered 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 integral to adaptive management. The critically important activities of implementation, monitoring, and adaptive management should be developed in consultation with stakeholders and reviewed by scientific peers. The involvement of the TIFP in these “Next Steps” has not been defined by the State of Texas and, therefore, will not be discussed in detail in this document.

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2. Ecological Setting

Given the wide diversity of aquatic ecosystems in Texas (Edwards et al., 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 flow conditions necessary to maintain a sound ecological environment will be tailored to each sub-basin, consistent with the overall goals of the TIFP.

2.1 Overview of Diversity of Texas Characteristics

A series of maps that illustrate the relevant characteristics of Texas may be found at: http://www.lib.utexas.edu/maps/texas.html. 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 *Aquifers of Texas* map delineates major, minor, and significant alluvial aquifers and provides information on their functioning, history, and importance (BEG, 2001). 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; information on natural and anthropogenic factors affecting plant associations, species richness, and the natural regions of the state is provided (BEG, 2000). The *Land-Resource Map of Texas* delineates land resources based on ground-water recharge, mineral, physical property, land form, dynamic process, and biological resource (wetland) units; information on importance and use of each unit is summarized (BEG, 1999).

Texas has approximately 307,385 km (191,000 miles) of low- to medium-gradient, warmwater 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 cm (50 inches) per year in the east to less than 25 cm (10 inches) per year in the west. Stream flows are directly related to episodic rainfall-runoff events, although the base flows of some Texas rivers and streams are groundwater dependent (spring-fed), while 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, geology, etc. found within the state's borders. A recent publication on biodiversity in the U.S. 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 et al., 1991). Native fish communities consist entirely of warmwater species, and their diversity reflects transitions from a Mississippi Valley fauna to the north and east to a Rio Grande fauna to the south and west (Conner and Suttkus, 1986). Consequently, east Texas rivers have diverse communities while rivers in west Texas are more depauperate (Edwards et al., 1989; Linam et al., 2002). The native stream fish fauna in Texas 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 et al., 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 (CITE?). In addition, the biogeographic origins of the faunal elements found in Texas streams are equally diverse with representatives being known from the Gulf Coastal Plain, Chihuahuan Desert, Great Plains, and the Neotropics (CITE). Similar to the fishes, invertebrate diversity and densities are higher in eastern Texas when compared to those of the western portion of the state (CITE). Anadromous organisms (e.g., river shrimp or "prawn") may travel far upstream into rivers, streams, and spring systems to complete their life cycle (Bowles et al., 2000). Texas is also not without its share of non-native 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 anthropogenic 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 non-point or point source pollution (CITE). Instream and riparian habitats have been altered by land-use practices, channel modifications, and changes to hydrologic regimes from construction of dams and their operation, diversion of surface water, and pumping of groundwater. Indeed, all of the major rivers in Texas are regulated to some extent by the water supply operations of the 211 major reservoirs (defined as those with a conservation storage capacity greater than 5,000 acre-feet), only one of which was built before 1900 (CITE). Some of these reservoirs also provide flood control and generate hydroelectric power. Non-native species introductions have altered the composition of lotic assemblages and in some instances have negatively influenced native species within a drainage or sub-drainage. Two recent assessments document changes in Texas fish assemblages (Anderson et al., 1995; Hubbs et al., 1997).

2.2 Overview of Riverine Components

The SB2 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, geomorphology, and water quality. Connectivity, scale, and dimension (see Section 2.3) are 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.

2.2.1 Biology

The biological component of instream flow studies includes developing an understanding of relationships between aquatic communities, life histories, habitat (e.g., instream, riparian) and the physical processes that create and maintain system habitat, water quality, and hydrology (Bovee et al., 1998; Annear et al., 2004). Riverine communities include freshwater and estuarine fishes and other vertebrates (e.g., 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 (CITE). 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. These organisms offer important 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 natural flow regimes. 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 et al., 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 (CITE).

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 µS/cm in east Texas to more than 100,000 in some west Texas streams (CITE). Altering the flow regime may change water quality and create a system that favors a non-characteristic assemblage. Elevated water temperatures or low dissolved oxygen concentrations can lead to fish kills or uninhabitable zones. Tolerance levels to low dissolved oxygen, for example, vary among species and taxa.

The life history and ecology of lotic organisms must be considered in the evaluation of 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 (e.g., nocturnal vs. daytime), and temperature regime is essential to understanding growth. Data on habitat use of prey items may also provide valuable information. Ensuring reproductive success involves many habitat considerations (current velocity, depth, substrate composition and embeddedness, cover, area, etc.) for spawning adults, eggs, fry, and juveniles; spawning behavior or reproductive mode (Johnston, 1999); and water quality issues (e.g., temperature cues). Other issues (e.g., migration patterns) associated with life history strategies may be important in some systems.

Temporal considerations (i.e., spawning season, timing with peak flows, photoperiod, etc.) also relate to life history strategies (Stalnaker et al., 1996). With respect to inter-annual (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 needs less frequently. Intra-annual (within a year) variation in flows is important to organisms that respond to the seasonal peaks and valleys of natural flow regimes for spawning or migratory behaviors. Scientists making recommendations on flow regimes must be cognizant of temporal considerations to incorporate inter-annual 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 clearly 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.

2.2.2 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. The characteristics of hydrology, which define the flow regime, include the magnitude, duration, timing, frequency and rate of change (Poff and Ward, 1989; Richter et al., 1996).

Hydrologic time series are important to assessing potential impacts to other riverine components. Daily time steps or shorter may be needed to address biological processes such as habitat use and spawning. Flows downstream from hydropower facilities may vary profoundly on an hourly basis, which may be important in the assessment of habitat availability and utilization. Dissolved oxygen concentrations vary diurnally and may be influenced by daily or hourly time steps. Larger time steps (months, years) are more suitable for addressing physical processes. Hydrologic time series can be developed to reflect historical flow conditions, natural flow conditions, and proposed project conditions. Development of these time series will facilitate comprehensive assessment of potential impacts to fish and wildlife resources through alternatives analysis.

In a basin-level assessment, the hydrologic network (geography of flows) is important to understand. Watershed contributions, water rights 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 current velocities and depths resulting from the channel morphology and discharge through the channel. Hydraulic conditions are important for describing instream habitat since many aquatic organisms show preferences for particular combinations of velocities and depths. A hydraulic model can be used to describe how the distribution, direction, and magnitude of velocities and depths changes with stream flow. Indeed, a major effect of hydrologic alteration is a change in the hydraulics that directly influence habitat.

2.2.3 Water Quality

Water quality parameters including temperature, dissolved oxygen concentrations, 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. Water temperature has a significant influence on growth (metabolic rate), survival (e.g., lethal temperatures), and reproduction (e.g., spawning cues and egg incubation) of stream fishes and macroinvertebrates because these organisms are cold-blooded (Armour, 1991). Temperature ranges tolerated by organisms vary by taxa and life-stage. Factors that influence temperature include streamflow, channel width, thermal inputs, riparian shading, and current velocity. Dissolved oxygen influences survival and distribution of lotic biota since many organisms have specific dissolved oxygen requirements. 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.

2.2.4 Geomorphology

Geomorphology includes those physical processes that form and maintain stream channels and habitat, flush fine sediments, and transport sediment loads. 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 effect on the physical features of a river system than individual, small-magnitude events. However, large flow events occur less frequently than small flow events and their overall effect is often less than the cumulative effect of more moderate flow events that occur with greater frequency (CITE). 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 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 the development and maintenance of in-channel habitats. Although smaller in magnitude than overbank flows, high pulse flows occur more frequently and therefore play a more active role in sculpting within channel habitats (CITE). Overbank flows play a critical role in the development and maintenance of riparian areas and floodplain habitats. The duration, rate of increase and decrease, and sequence of flow events also influences physical processes and may have important biological consequences. For example, during the receding portion of the hydrograph associated with 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 of coarse sediments in reservoirs or land use changes. When either the hydrologic or sediment regime is altered, an understanding of geomorphic processes is required in order to evaluate potential consequences to the physical features of a river.

2.3 Connectivity, Dimension, and Scale in Stream Systems

Connectivity, dimension, and scale are important considerations in the development and execution of many aspects of sub-basin studies including the development of conceptual models, the 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 and pervasive, encompassing physical, hydrological, chemical, and biological processes; the dimensions of connectivity occur 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 transport and processing of nutrients and organic matter, migratory species, and physical processes such as sediment transport. Water quality characteristics 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 while baseflows in others may be supported by springflows and seeps. Temporal aspects are related to the timing of events that mediate connectivity (e.g., overbanking flows that connect instream processes with floodplains) and the life history of aquatic and riparian species.

Anthropogenic influences have the potential to affect instream resources through these connections. For instance, alterations to landscapes through urbanization and floodplain development may have substantial affects on instream processes even while being 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 et al., 2000). Reductions in high flow pulses and overbanking 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 affect by reducing levels in aquifers that may provide baseflow to streams. At a smaller scale, water diversions can reduce flow, making shallow, erosional habitats unsuitable, but also affecting longitudinal connectivity by inhibiting upstream migration by some aquatic organisms.

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 et al., 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 et al., 1981; Elwood et al., 1983). The length of a given spiral is a function of transport rate and physical retention and biological uptake. Stazner and Higler (1986) put forth the stream hydraulics concept to explain biological zonation in the longitudinal dimension as related to clear changes in hydraulic conditions.

Studies have also led to an expansion of the concept into lateral and vertical dimensions. The flood pulse concept describes the process by which matter (nutrients, sediments, biota) is regularly exchanged between the river and the floodplain (Junk et al., 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. Addressing the vertical and lateral dimensions, the hyporheic corridor concept recognizes the importance of subsurface-surface interactions (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, streams waters are cooler in the winter than in summer months, and dissolved oxygen concentrations in streams may decrease at night because of plant and algae respiration. Stream flows also vary seasonally reflecting the seasonal patterns in precipitation and evaporation, as well as anthropogenic 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 previously experienced in Texas. Consequent to the hydrologic dynamics, changes in hydraulics and geomorphology influence habitat dynamics and thus biological processes.

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 et al., 2002). Relevant scales for lotic species of fish and invertebrates can include basin or watershed, stream reach, channel unit or mesohabitat, and microhabitat (Poff, 1997). For example, at the microhabitat scale many flow-dependent species demonstrate preferences for faster current. At the mesohabitat scale, riffle-dwelling species utilize riffles almost exclusively while others may use them only at night. At the reach scale, riparian conditions may influence trophic structure (e.g., the presence of sufficient particulate organic matter input such as leaf matter to facilitate a shredderdominated 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 (e.g., Frissell et al., 1986; Imhof et al., 1996; Harby et al., 2004; Brierly and Fryirs, 2005). Unfortunately, there has been little standardization of terminology, which may contribute to confusion during multidisciplinary studies (Benda, 2002). In order to insure 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 studes. This nomenclature is shown in Figure 2.1, along with nomenclatures from other researchers for comparison purposes. The nomenclature of Frissell et al. (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 et al. (1996) are adapted for larger river systems and include explicit recognition of the effect of the watershed on river processes at larger scales. Harby et al. (2004) reflect a habitat modeling perspective. Their nomenclature also includes a unit called “picohabitat” (not shown in Figure 2.1) whose dimension is on the order of centimeters. Brierly and Fryirs (2005) reflect the perspectives of fluvial geomorphology.

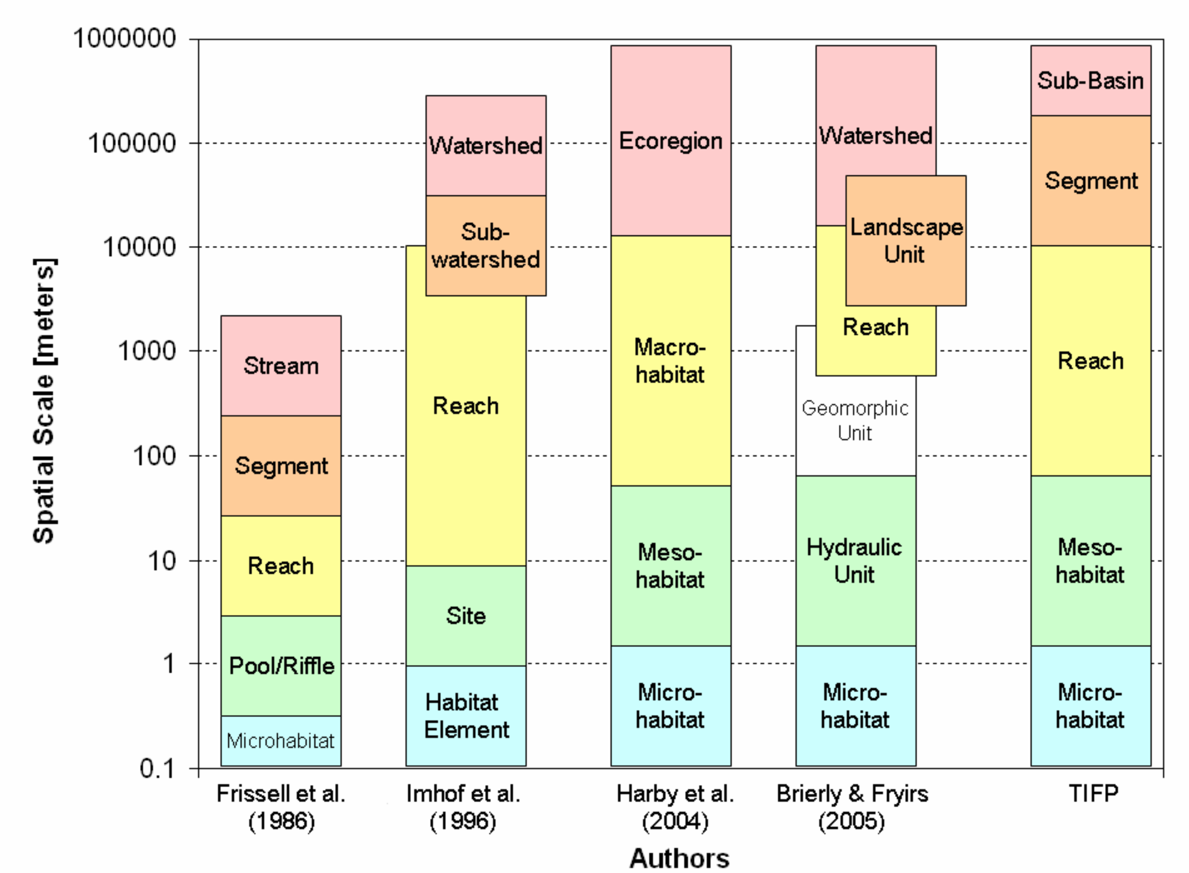

Figure 2.1. Nomenclatures describing the spatial scale of riverine ecosystems.

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 as defined in Figure 2.1.
Definitions of spatial scale units adopted by the TIFP 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 TCEQ river segments. 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 (hydrologic/hydraulic, biological, geomorphic, water quality) bounded by breaks such as the confluence of major tributaries, significant geomorphic features, etc. 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 et al., 2002). For smaller streams, mesohabitats are known by such names as pool, riffle, run, chute, etc.
e. **Microhabitat**: Zones of similar characteristics within a mesohabitat unit. Differentiated by aspects such as substrate type, water velocity, and water depth.

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3. Peer Review and Stakeholder Input

While the Agencies have the statutory responsibility to carry out the Texas Instream Flow Program (TIFP), public input is critical to the development and implementation of instream flow recommendations. To ensure meaningful participation that results in public confidence in both the science of instream flow studies and the process that creates instream flow recommendations, the Agencies are committed to program transparency, stakeholder participation, and scientific peer review.

The Agencies will make every effort to ensure that the activities of the TIFP are transparent to the public and that there will be plenty of opportunity for public input. Public documents, such as this one, will describe the approach and methods of the TIFP. For all river studies, final study designs, reports, and supporting documents will be available to the public. The Agencies have developed and continue to maintain a web site (http://www.twdb.state.tx.us/instreamflows/index.html) documenting TIFP activities.

Stakeholders will be directly involved in the process of developing goals and study designs for specific instream flow studies. The National Research Council report (NRC, 2005) noted that stakeholder involvement in goal setting is particularly important given the potential for conflict among water users and recognized the knowledge of Texas rivers that stakeholders will bring to the table. The stakeholder process will require the formation of basin-specific groups with broad representation that will advise the agencies throughout the course of individual studies. Likely parties include but are not limited to public agencies, regional water planning groups, river authorities, municipalities, industries, agricultural interests, commercial and sport fishing interests, recreation interests, environmental groups, public interest organizations, and academic institutions. Input shall be sought on both technical and non-technical issues. During this process, the Agencies will ensure consistency with statewide goals as well as with state and federal legislation and policies.

Scientific peer review is recognized as an important part of an instream flow assessment program (Arthington et al., 1998; NRC, 2005). The Agencies will make every effort to submit individual study designs and reports and overall program documentation of the TIFP for scientific peer review. In addition, research findings related to instream flow assessments will be submitted for publication in peer-reviewed journals. The original version of this document was submitted for peer review by national experts (NRC, 2005). Subsequent revisions and modifications of this document will also be submitted for peer review. Incorporation of scientific peer review of the TIFP is intended to increase public trust and improve the technical soundness of products and recommendations.

3.1 Opportunities for Stakeholder Input

Sub-basin instream flow studies lend themselves to stakeholder participation throughout the study process. As depicted in Figure 3.1, stakeholder input will be sought in all steps of the instream flow study process..

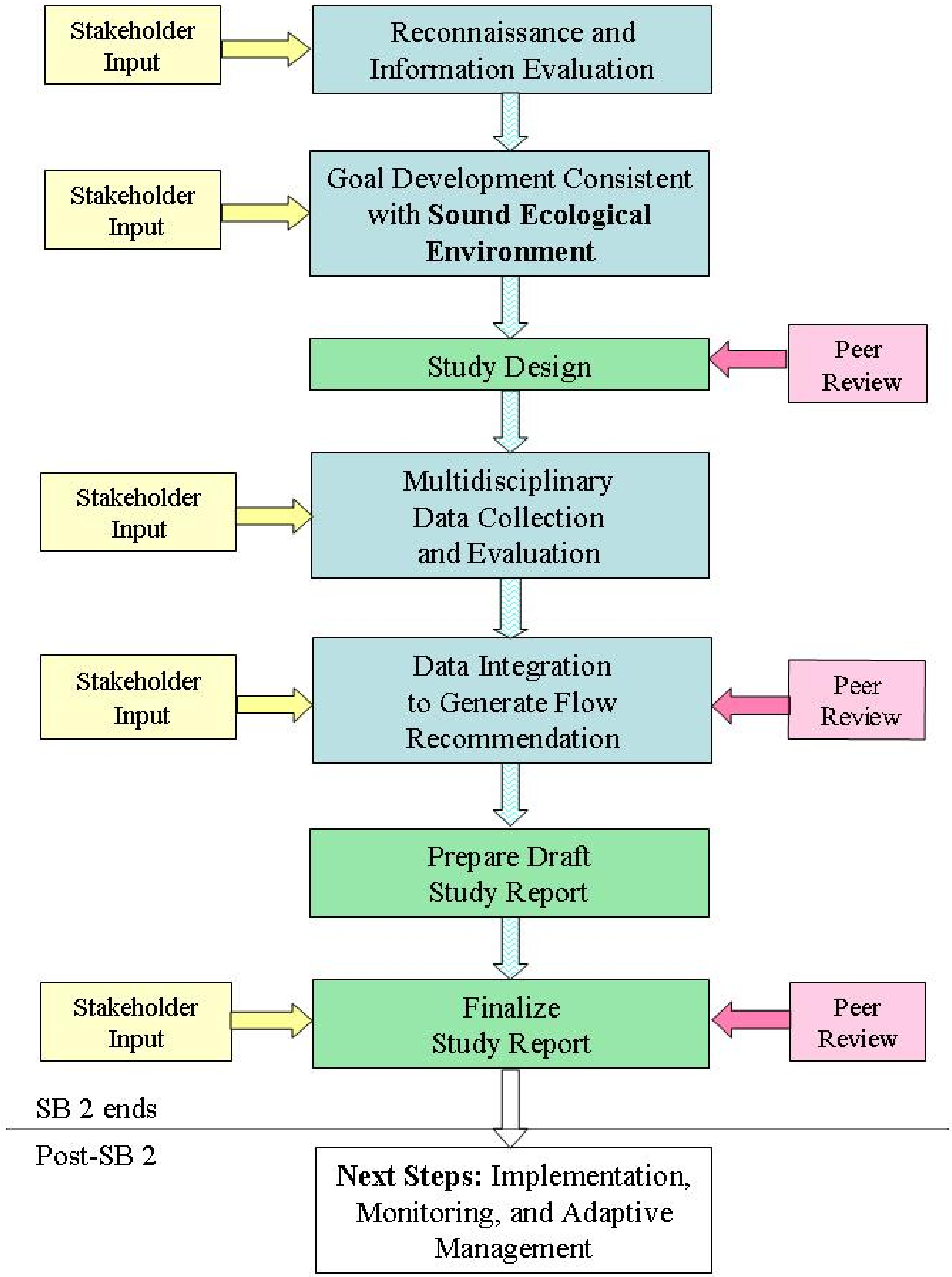

Figure 3.1. Sub-basin specific study steps for the Texas Instream Flow Program (TIFP).

Examples of stakeholder input that will be sought early in the sub-basin process include assisting the Agencies in identifying specific study areas within sub-basins, determining management goals and the suite of indicators for a study, applying the definition of "sound ecological environment" to the sub-basin or segment, and developing a timeframe for the design and performance of the study recognizing all statutory and practical resource limitations. During later stages, stakeholder advice will be critical in balancing goals and developing the final instream flow recommendations.

Direct stakeholder technical and/or financial participation in the performance of the studies is also sought by the Agencies and offers the opportunity to maximize resources and assist in meeting statutory deadlines. It is anticipated that stakeholders may hold specialized expertise about specific basins and may be instrumental in securing additional funding sources. Additionally, the TIFP was designed so that instream flow studies could be conducted by qualified third parties or stakeholders. With the Agencies' oversight, third parties may perform instream flow studies that apply the state methodology and these studies will be included as part of the official TIFP.

Finally, while not part of the TIFP, it is envisioned that stakeholders may also be involved in the implementation of instream flow recommendations, as well as future monitoring and adaptive management strategies. The TIFP provides the tools to develop instream flow recommendations. However, implementation of instream flow requirements is beyond the scope of the TIFP.

3.2 Peer Review

In order to ensure public trust in the science behind instream flow recommendations, the activities of the TIFP will be peer reviewed. The National Research Council 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 (NRC, 2005). Results of these reviews must then be communicated to the "involved scientists, instream flow scientific community at large, and stakeholders" be assessed through "an independent, interdisciplinary, periodic peer review process" (NRC, 2005).

The Agencies intend to establish a core peer review team consisting of independent experts in the fields of biology, hydrology and hydraulics, water quality, and geomorphology (physical processes). Particular situations may require the Agencies to bring in experts from other disciplines. The diversity of sub-basin studies will require varied approaches in conducting the instream flow studies, and the Agencies must assure that models and methods are applied appropriately. Peer review will provide critical input and assure interested parties that a sound science base is the foundation of these studies.

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4. Study Design

Sub-basin study designs will necessarily flow from the statewide goals and objectives of the TIFP as outlined by Senate Bill 2 and tackle the specific issues associated with a defined study area. The evolution of this approach is outlined in Table 4.1, which begins with the overall legislative directive and narrows down to a specific sub-basin in question. Key to developing a consistent approach for the TIFP 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 (e.g., 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 are critical to establishing sub-basin study goals and objectives, which will form the foundation of a suitable study plan. 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.

4.1 Reconnaissance and Information Evaluation

Prior to initiating program efforts, the geographic scope of the study area will be identified. For TIFP priority studies (described in TIFP 2002), a study area will consist of a sub-basin (portion of a major river basin) composed of several TCEQ stream segments as defined in Appendix A of the Texas Administrative Code §307.10(1). Study areas will extend from the river channel to the riparian and floodplain area of the segments and include consideration of tributaries, floodplain areas, groundwater interactions, and watershed areas.

During the reconnaissance and information evaluation step, existing data for the study area are collected and evaluated. This is done to determine what historic conditions may have been like, to evaluate the current understanding of the system, and to 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, preliminary data collection and reconnaissance efforts will be undertaken. Reconnaissance efforts will be focused on familiarizing agency personnel with the study area and current condition of the river ecosystem. The location of access points and potential study sites will also be identified. Data collection will focus on filling in gaps in the available data and establishing the “baseline” condition of the system.

Table 4.1. Summary of development of TIFP sub-bain 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, and
  - Define connectivity issues within the system.
- Evaluate biological communities:
  - Examine the integrity of the biological community,
  - Examine biodiversity within the system, and
  - 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 (e.g., 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,
- Through stakeholder process, define primary issues affecting instream flows, and
- 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, influx of sediment and nutrients, etc.) Once important indicators have been selected, a specific study plan with procedures and means for implementation can be developed.

Preliminary analysis of historical and reconnaissance data will be completed during this step, resulting in a summary of all data and analysis, including GIS data layers and conceptual models 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, historical conditions for the river will be estimated, as well as a comprehensive list of stressors.

4.1.1 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. A substantial amount of data has been collected on various aspects of stream ecology for most of Texas' rivers. These data, however, were collected for a variety of purposes by various public agencies, private consultants, academic researchers, and others. Given the interdisciplinary nature of instream flow studies, relevant data span several academic disciplines. The primary objective of this task is to compile and organize existing historical information on the hydrology, biology, physical habitat, and water quality of the proposed study area. This approach was employed for the Guadalupe (Longley et al., 1997) and Trinity rivers (Kiesling and Flowers, 2002). The Trinity River report included an ArcView Geographic Information System (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 TIFP sub-basin studies. Agencies with such programs include the United States Geological Survey (USGS), Army Corps of Engineers (COE), United States Fish and Wildlife Service (USFWS), Environmental Protection Agency (EPA), Natural Resource Conservation Service (NRCS), and National Oceanic and Atmospheric Administration (NOAA).

The USGS is the primary federal agency responsible for collecting, monitoring, and analyzing natural resources data. In cooperation with the TWDB and other local partners, the USGS maintains a network of surface water flow gauges within the State of Texas. This network provides flow data invaluable for hydrologic studies. In order to develop rating curves for gauge locations, the USGS collects channel cross sectional data which may also prove useful for geomorphic investigations (Juracek, 2000). The USGS periodically collects water quality and sediment data at some gauge sites. They are a source of aerial photography and digital elevation and topographic maps. They have also completed studies on water quality and quantity issues.

The COE 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 401) and cooperate with local entities on flood control and aquatic restoration projects. The COE conducts hydrologic and hydraulic modeling in support of the National Flood Insurance Program administered by the Federal Emergency Management Agency. Information available from the COE includes studies and data related to dams, operation of reservoirs, restoration projects, and flood studies on specific river segments.

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

The NRCS provides technical assistance to land owners, communities, state and local governments, and other federal agencies to help them conserve soil, water, and other natural resources. The NRCS is a source of aerial photography, digital orthophotos, soils maps and surveys, and information related to sediment processes.

Responsibilities of NOAA include maintaining and improving marine and coastal ecosystems, delivering weather, climate, and water information, and understanding the science and consequences of climate change. NOAA 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 TWDB has conducted planning studies related to instream flow needs downstream of proposed water supply reservoirs. Through Research and Planning Funds, they have 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 TWDB, is the state's clearinghouse for maps, aerial photos, and digital natural resources data. TPWD has completed studies related to riparian and aquatic species, as well as completing or cooperating on instream flow studies. TCEQ administers the water rights permitting process that includes hydrologic and ecological analyses associated with requests to impound and divert water. TCEQ 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 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 et al., 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 TCEQ's primary partners in the Texas Clean Rivers Program and engage in monitoring that may include flow gauging, 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 a Geographic Information System, 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.

4.1.2. Conduct Preliminary Field Surveys and Analysis

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, anthropogenic impacts, and existing fish and wildlife resources.

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

Land Surveys: Access points for launching boats, placing remote sensors, survey points, etc. need to be visited over land before final determinations on study site and boundary selection can be made. Preliminary assessment of riparian and floodplain areas will also be made.

Boat Surveys: Longitudinal surface surveys should be performed for each study area. Surveys may be performed for the entire study area or may involve the selection of representative reaches. During the survey, efforts should be made to delineate and estimate mesohabitat features, overhead cover, substrate, and instream cover such as woody debris and boulders throughout the stream segment. Cross-sectional measurements should be taken at regular intervals along the channel. The longitudinal extent of mesohabitat types can be measured by logging longitudinal position along the channel with Global Positioning System

(GPS) instruments and feature coding the upper and lower boundaries of mesohabitats. These mesohabitat surveys should be performed when flows are at or less than median and habitat features are relatively easy to identify.

Preliminary field surveys and analysis

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 available historical data, and selecting study sites for intensive technical studies. A more detailed description of technical activities is provided in Chapters 5 through 8. Activities in the four disciplines will include:

Hydrology: Analyze historic gauge 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 particularly flow sensitive). These species may include those considered imperiled. Biota of interest will 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 historical condition of stream and riparian biota will be assessed.

Geomorphology: Activities related to geomorphic investigation will include analysis of historical data. Field surveys will focus on preliminary channel, bedform, and bank assessment and identification of active channel and floodplain processes. Staff will document any evidence of changes in sediment regime and their causes. Geomorphic classification of the river segment will begin. Results will be constrained by limited historical data and the short timeframe available to observe large spatial and temporal scale processes.

Water Quality: Agency staff will 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 to provide a picture of the current condition.

4.1.3. Develop Conceptual Models

Using the available historical 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 (biology, water quality, etc) thereby aiding in the identification of 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 the development of study designs (Cooperative Research Centre for Freshwater Ecology, 2001) because they provide:

- Clear articulation of how rivers function,
- Improved communication with the non-scientific community,
- Visual description of existing 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 the selection of 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 TB4.1.1 in Text Box 4.1.

4.2 Goal Development and Study Design

During the second step of a sub-basin instream flow study, stakeholders and the Agencies will develop study goals. These study goals will be consistent with statewide goals and objectives. Stakeholders and the Agencies will collaborate on this step.

4.2.1 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 future state 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 (see Text Box 4.1).

Once sub-basin goals are defined, objectives will be developed. The objectives will describe what ecological outcomes are required to achieve study goals. For example, in Australia, the goal of "a healthy and productive River Murray" led to several objectives (see Text Box 4.1). 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.

4.2.2 Indicators

Sub-basin objectives lead quite naturally to the choice of indicators. See Text Box 4.2 for a description of how ecological indicators may be used for TIFP studies. 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 for the study area and stakeholder concerns. This list will then be pared down to ecologically-significant indicators that are directly related to components of the flow regime. As an example, again consider the River Murray described in Text Box 4.1. Based

Text Box 4.1. Example of goals, objectives, indicators, and conceptual models for the Murray-Darling Basin, Australia. (CITE)

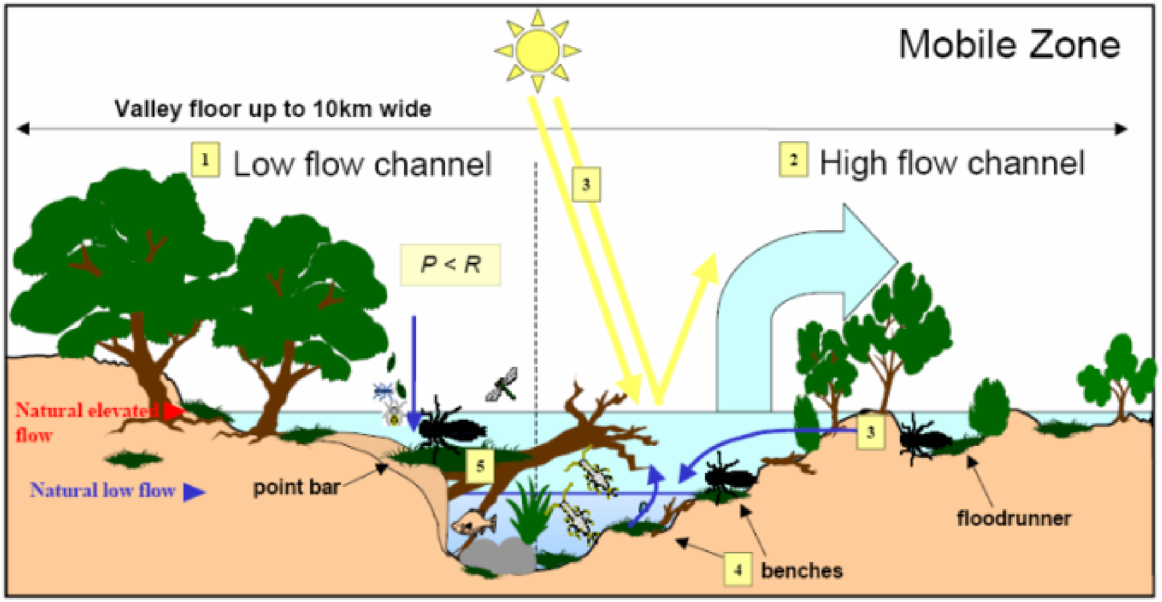
According to ADEH (2006), the Murray-Darling Basin (MDB) is one of Australia's largest drainage divisions with just over one million square kilometers. The basin includes the three largest rivers in Australia — the Darling River at 2740 km, the Murray at 2530 km, and the Murrumbidgee at 1690 km. The basin is very important for its biodiversity. At the time of European settlement, about 28 per cent of Australia's mammal species, 48 per cent of its birds and 19 per cent of its reptiles were found there. Of these species, 20 mammals are now extinct and 16 mammals and 35 birds are nationally endangered. There are some 30,000 wetlands in the basin and many are suffering because of human activities. Over-allocation of water, changed water flows, land clearing, increasing instream and dryland salinity, weeds, and exotic species are having increasingly negative effects on ecological communities and their interactions.

Conceptual models of the MDB were developed for eight different geomorphic process zones (CRCFE, 2001). Zones included headwater pool, confined, armoured, 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 TB1.1. Note that some of the terminology shown in this figure may be defined differently in Australia or be unique to Australia.

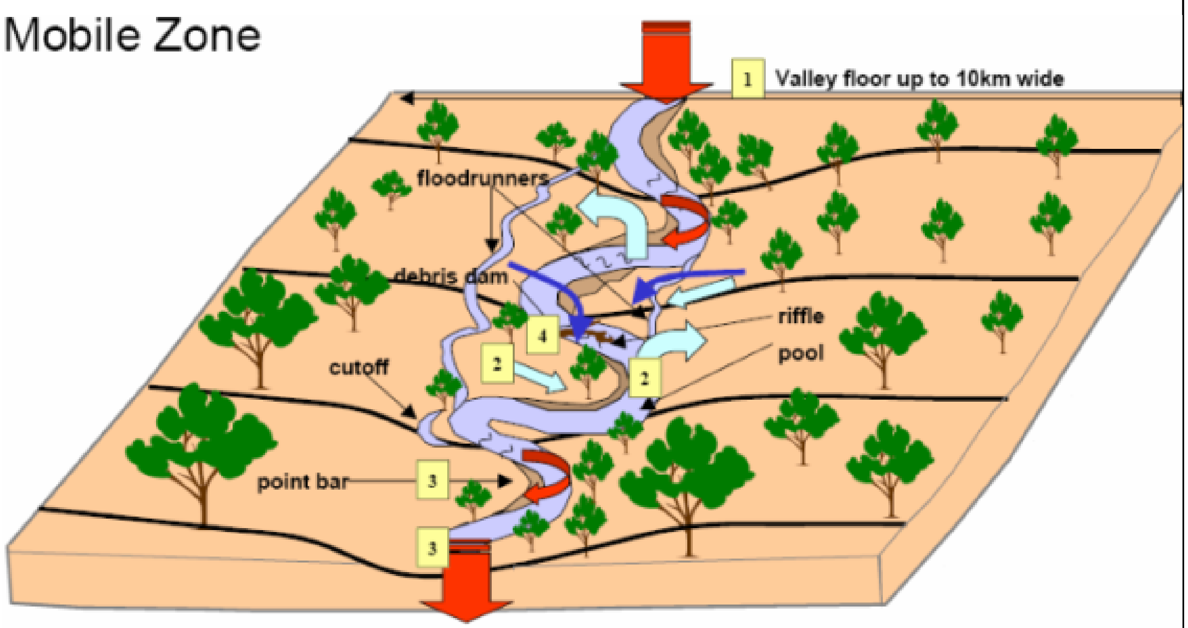
Collective efforts at all levels of government to restore the Murray to a healthy working river began in November 2003 (MDBC, 2005b). The national, state, and local governments involved in allocating the resources of the MDB adopted the vision of a healthy and productive River Murray as their goal. In 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; and
7. Manage flow-related water quality to sustain ecological processes and productive capacity (MDBC, 2005b).

Indicators related to these objectives are currently being developed. At present, a number of indicators have been approved for basin-wide application, including 13 indicators related to fish, three related to macroivertebrates, and 12 related to hydrology. 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 TB1.1.



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 flow channel is characterized 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 instream processes. **5** Fallen timber may create debris dams, trapping organic matter of various sizes, also 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, detritus, etc 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 TB4.1.1. Conceptual model developed for a portion of the Murray-Darling Basin, Australia (from CRCFE, 2001).

Table TB 4.1.1. Example indicators for Murray-Darling Basin, Australia (CITE).

Category	Sub-category	Indicator	Comments/Description
Hydrology[1]	High Flow	Number of 1 in 10 year floods	1 in 10 year annual return interval flood calculated for natural conditions.
	Low & 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-invertabrate[2]	Richness	Biodiversity indicated by the number of taxa.
		Pollution sensitivity score	Families observed are graded for sensitivity to pollution. The average of the grades is the score for the site.
	Fish[3]	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 mega carnivores	Proportion of individual fish (native and alien) at each site that are mega-carnivores (eat prey >15mm length).
	Riparian[4]	Waterbird breeding	Successful breeding in at least three years out of ten.
		Healthy vegetation area	55% of the Barmah-Millewa Forest in healthy condition.
Geomorphology[5]		Channel stability	Maintain current level of channel erosion.
Water Quality[6]		Total phosphorus	• upstream of Jingellic: < 20 µg/L • between Jingellic and Broken Creek confluence: 20-50 µg/L • between Broken Creek and Moama: 50-100 µg/L • between Moama and Barham: 20-50 µg/L • between Barham and Wakool Junction confluence: 50-100 µg/L • downstream of Wakool Junction: > 100 µg/L

Sources: [1]MDBC, 2003b; [2]MDBC, 2003c; [3]MDBC, 2003a; [4]for the Barmah-Millewa Forest only, MDBC, 2005a; [5]for the main channel of the River Murray only, MDBC 2005b; [6]currently being developed by an interstate process, these values for information purposes only, NSWDEC, 2006.

Text Box 4.2. Use of ecological indicators in TIFP basin-specific 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 the stakeholders in a particular sub-basin will be monitored at spatial and temporal scales that reflect the processes relevant to establishment and maintenance of a diverse and sustainable aquatic environment. Following the implementation of instream flow recommendations, long-term monitoring and assessment of the aquatic ecosystem using ecological indicators will ensue to measure progress towards achieving a sound ecological environment in a particular sub-basin. These indicators will be used to document the conditions, trends, processes, and phenomena associated with an 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 comparison of 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 TB 4.2.1. 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

Modified from Harwell et al., 1999.

Ecological indicators should be selected on the basis of their intrinsic importance (measure is the endpoint itself or highly relevant and interpretable), 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 et al., 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 at various levels in the ecosystem hierarchy 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.

on the objective of reinstating ecologically-significant elements of the flow regime, 13 hydrologic indicators were identified. 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.

During goal development, consideration will be given to 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 et al., 2000; Schofield et al., 2003). Instead, the goal for such rivers should be to improve their ecological condition. Palmer et al. (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 non-native 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."

With the available data and conceptual models, the Agencies will collaborate with stakeholders in evaluating the range of future states achievable for a specific river segment.

The Agencies will also provide input to stakeholders during development of objectives and indicators. They 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. Selection of goals, objectives, and indicators will also conform to applicable federal and state law, including the Federal Clean Water Act, Endangered Species Act, and Texas Administrative Code.

Goals, objectives, and indicators will consider existing programs such as the TCEQ Water Quality Standards for designated and undesignated stream segments in Texas (TAC §307.10(1) Appendix A and Appendix D). For example, for the Lower Sabine River, TCEQ has already established site-specific water quality uses and criteria for designated segments (Table 4.1) and several smaller tributaries (Table 4.2). In addition, the aquatic life uses are based upon additional criteria related to the condition of the river ecosystem (Table 4.3). These already existing criteria may be incorporated into goals, objectives, and indicators as relevant to identified instream flow issues given that they were developed within the context of the water quality regulatory program.

Table 4.1. TCEQ site-specific uses and criteria for the Lower Sabine River (from TAC §307.10(1) Appendix A).

TCEQ Segments		Uses			Criteria						
Sgt. No.	Segment Name	Recreation	Aquatic Life	Water Supply	Cl^{-1} mg/L	SO_4^{-2} mg/L	TDS mg/L	D.O. 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

Table 4.2. TCEQ site-specific criteria for tributaries of the Lower Sabine River (from TAC §307.10(4) Appendix D).

Tributaries to TCEQ Segments		Uses			Criteria						
Sgt. No.	Tributary Name	Recreation	Aquatic Life	Water Supply	Cl^{-1} mg/L	SO_4^{-2} mg/L	TDS mg/L	D.O. mg/L	pH range SU	Bacteria #/100ml	Temp. F
0503	Caney Creek	Contact Recreation	High					5.0		126/200	
0503	Unnamed tributary of Dempsey Creek	Contact Recreation	Inter-mediate					4.0		126/200	

Table 4.3. Definition of TCEQ Aquatic Life Use (ALU) subcategories (from Table 4 of TAC §307.7(b)(3)(A)(i)).

ALU Subcategory	Habitat Characteristics	Species Assemblage	Sensitive Species	Diversity	Species Richness	Trophic Structure
Exceptional	Outstanding natural variability	Exceptional or unusual	Abundant	Exception-ally high	Exception-ally 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

4.2.2 Formulate Study Design

Before completion of a study design, stakeholders and Agencies 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 condition, and 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.

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5. Hydrology and Hydraulics

As noted by Richter et al. (2003), a river's hydrologic flow regime is recognized as a ‘‘master variable’’ that drives variation in other components of the river ecosystem. Results of hydrologic and hydraulic evaluations play a key role in developing instream flow components. In addition to providing analysis of the hydrologic regime, these evaluations provide results that assist biological, geomorphic, and water quality studies. Statistical evaluation of hydrologic data will be used to develop all four instream flow regime components: subsistence, base, high pulse and overbank flows. Hydraulic modeling results provide crucial input data to habitat modeling during biological evaluation of base flows. Hydraulic modeling also provides an estimate of the extent of inundation during the evaluation of overbank flows.

Water diversions affect the flow regime, that is, the frequency, timing, duration, rate of change, and magnitude of streamflow. An evaluation of hydrologic data provides an assessment of the alteration of hydrologic regimes. Hydrologic time series data are analyzed to assess current conditions, quantify alteration in quantity and timing of flows, and characterize the physical behavior of water in the system at an ecologically relevant scale. Ecological responses to altered hydrologic and hydraulic conditions will be investigated. Low flow statistics such as 7Q2 support development of subsistence flow recommendations (CITE). Median and percent exceedence flow statistics support development of base flow recommendations. Flow statistics are also used to describe wet, normal, and dry hydrologic conditions. High flow and flood frequency statistics support development of high pulse and overbank flows. Hydrologic evaluation methods are discussed in Section 5.1.

Hydraulic modeling will be conducted in support of some flow component recommendations. Suitable base flows will be determined by biological evaluation of habitat conditions. To assist habitat modeling efforts, within-channel hydraulic characteristics over a range of flows will be determined with 2-D hydraulic modeling. Results will be used to determine habitat relationships with flow. A 1-D hydraulic model will be used to estimate inundation of riparian areas and assist in the development of overbank flows. Additional hydraulic modeling may be conducted in response to concerns related to sub-basin studies. Hydraulic modeling techniques are discussed in Section 5.2.

5.1 Hydrologic Evaluation

A hydrologic evaluation of a river's flow regime is required in order to evaluate 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 thirty or more years. During this extended period of modification, significant changes that should be considered when making instream flow recommendations may have occurred. For example, since 1964 Canyon Dam on the Guadalupe River has altered the thermal regime of a portion of the river immediately downstream of the dam. Under current conditions, returning this portion of the river to a warm water condition more typical of the region may not be feasible or desirable.

Across the state of Texas, natural flow regimes exhibit tremendous variability and include seasonal periods of low flow, short duration floods, stable base flows, etc. These large variations can be attributed to the geographical variation and size of Texas, which experiences disparate regional precipitation patterns (58 inches per year in coastal east Texas to as little as 8 inches in arid, far 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. More than 200 major dams have been constructed for flood control and/or municipal supply. The ratio of available reservoir storage volume to natural rainfall-runoff volume equals nearly three for river basins in the eastern half of Texas (Graf, 1999).

Many aquatic species have specific habitat and life history requirements that are intimately linked to seasonal trends and natural flow regimes (Richter et al., 1996). Aquatic ecosystems can respond to alterations in the natural flow regime but usually at 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 also have spawning activities keyed to high flow events. Opportunistic 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; negative impacts on upstream fish communities have also been documented (Winston et al., 1991).

The health and maintenance of various riparian areas, hardwood bottomlands, and associated wetland ecosystems is 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 as rivers, streams, and riparian areas cumulatively assimilate large volumes of nutrients and organic materials from both natural and anthropogenic sources, such as wastewater and non-point source runoff.

In order to protect river ecosystems, the National Research Council recommended the TIFP specify four hydrologic flow components (NRC, 2005). These components are overbank, high pulse, base, and subsistence flows. Each of these flow components 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 TIFP will recommend a set of instream flows that include these four components. For a specific sub-basin, additional flow components may be required.

The maintenance of riparian areas is dependent on the timing, duration, and intensity 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 pulse flows are important for channel maintenance. Accumulation of sediments or vegetative encroachment may occur if high pulse flows 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 and high pulse flows create and maintain physical habitat features within the channel. These greater magnitude flow 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 flows to streams, cause reductions in habitat diversity and availability, loss of stream productivity, and alterations to trophic and community structure. Reduced base flows can 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. In some cases, however, humans may have increased the duration and frequency of these events. This can have serious impacts on 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 survival of many species. Consequently, populations of aquatic organisms needed for recruitment may not exist once stream flows return to normal base levels. The threat of significant, adverse impact 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. Inter-basin 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 hydrologic 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 inter-annual flow variations (Richter et al., 1996). Hydrologic evaluation in support of TIFP studies will include analysis of both historical and "naturalized" flow data. Historical flow data, described in Section 5.1.1, are available from streamflow gauging 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 5.1.2.

5.1.1 Historical Flow Data

Historical stream flow information will be compiled from USGS and other gauging 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 wet, dry, and average years.

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

A gauge site may not be present in the immediate vicinity of a study site; however, the existing Core Network of USGS gauging sites is designed so that each significant watershed contains its own unique gauging station. The Core Network also ensures that there are sufficient "representative" watersheds gauged throughout the state such that flow on an ungauged watershed can be estimated with reasonable accuracy. Within the same river, and within reason, watershed area multipliers are used to compare projected flow at a study site to the flow measured at the nearest upstream or downstream gauge. 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 (DEM) or National Elevation Datasets (NED) at 10- or 30-meter resolution published by the USGS to delineate watershed boundaries. If DEM or NED data are unavailable, Digital Raster Graphic or USGS 7.5 minute topographic quad sheets will be used to assist delineation of watersheds. Spatial representation of rivers and lakes (based on USGS topographic quad sheets corrected using aerial photography) can be obtained from the Texas Natural Resource Information System web site (http://www.tnris.state.tx.us/). A lot of this work can be handled easily in a GIS environment.

5.1.2 Naturalized Flow Data and Water Availability Modeling

Since natural river flow regimes can no longer be observed on most rivers in Texas, the natural flow regime, or natural baseline condition, must be estimated from available data. This can be accomplished by accounting for reservoir attenuation, removing known return flows, and adding diversions into a historical flow record. 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 to determine naturalized flows than estimating and accounting for reservoir attenuation and losses.

Water availability models (WAM) used for water rights permitting in Texas can be used to remove the estimated effects of human diversions from historical flow data. At the present time, however, these models utilize monthly time steps. Monthly summary volumes are inadequate for evaluation of instream flows because they do not account for hourly or daily flow variation. Hourly and daily time scales are important to ecological health and should be considered when evaluating a permit application. Generation of a reasonable, synthetic, hourly historical dataset is not warranted or feasible for most projects (except perhaps for projects involving hydropower operations). Therefore, naturalized flow data with a daily time scale will be sufficient for most TIFP studies.

Daily average naturalized flows will be calculated by distributing monthly WAM naturalized flow output according to the pattern of daily data from the nearest river gauging station. The volume of daily average flows measured at the gauge station will be summed over each month. A flow distribution curve of daily flows normalized to the monthly sum will be used to distribute the monthly WAM naturalized flow across each day of the month. Daily naturalized flows provide the baseline for estimating the effect of all allocated water rights by applying each project's operating rules to the daily time series.

Due caution will be exercised when interpreting the results. The daily distribution of naturalized flows is generated from flow gauge data that are measured in a system that may have already been impacted by extractions. The shape of the hydrograph may be altered by many factors, including water rights extractions, in-channel impoundments, and changes in the watershed that affect timing and quantity of runoff (for example, an increase in impervious cover associated with urban development).

5.1.3 Flow Frequency Analysis

Frequency analysis on the time series of flows can provide a good idea of both the "flashiness" of the river and the degree of human impact. Flow data for naturalized, pre-development historical, or current 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 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 unregulated and regulated conditions on the same graph, as shown in Figure 5.1.

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 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.

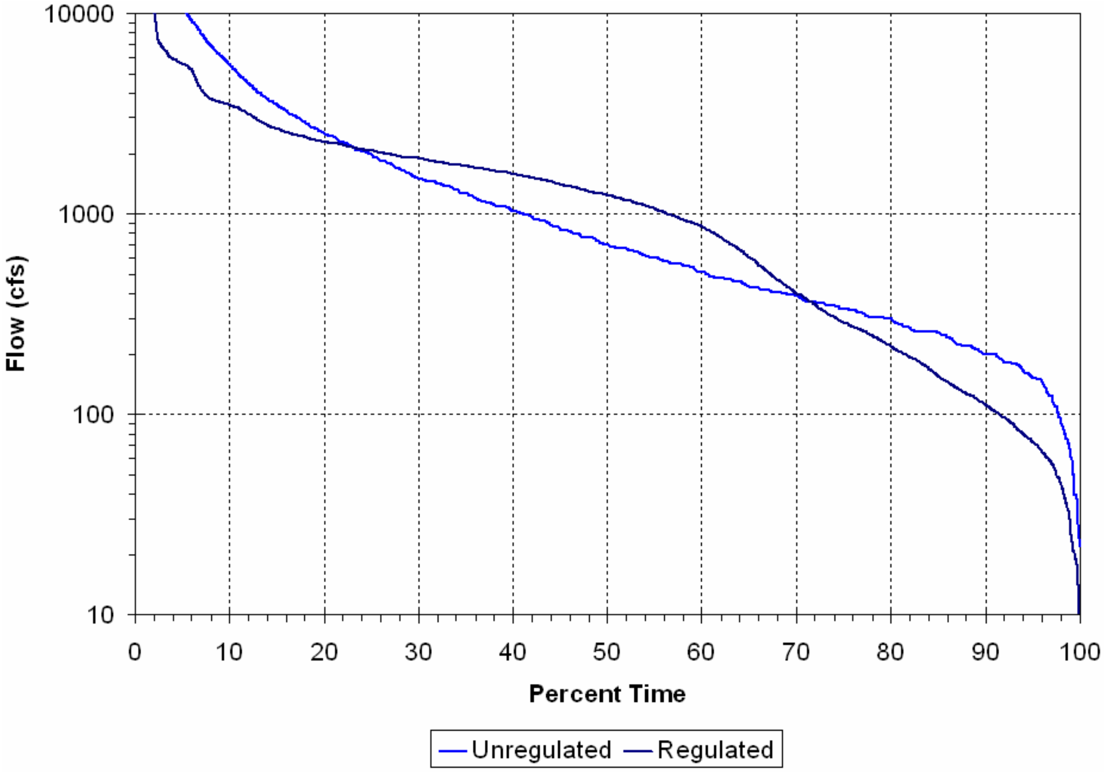

Figure 5.1. Flow duration curve calculated from daily data for unregulated and regulated conditions.

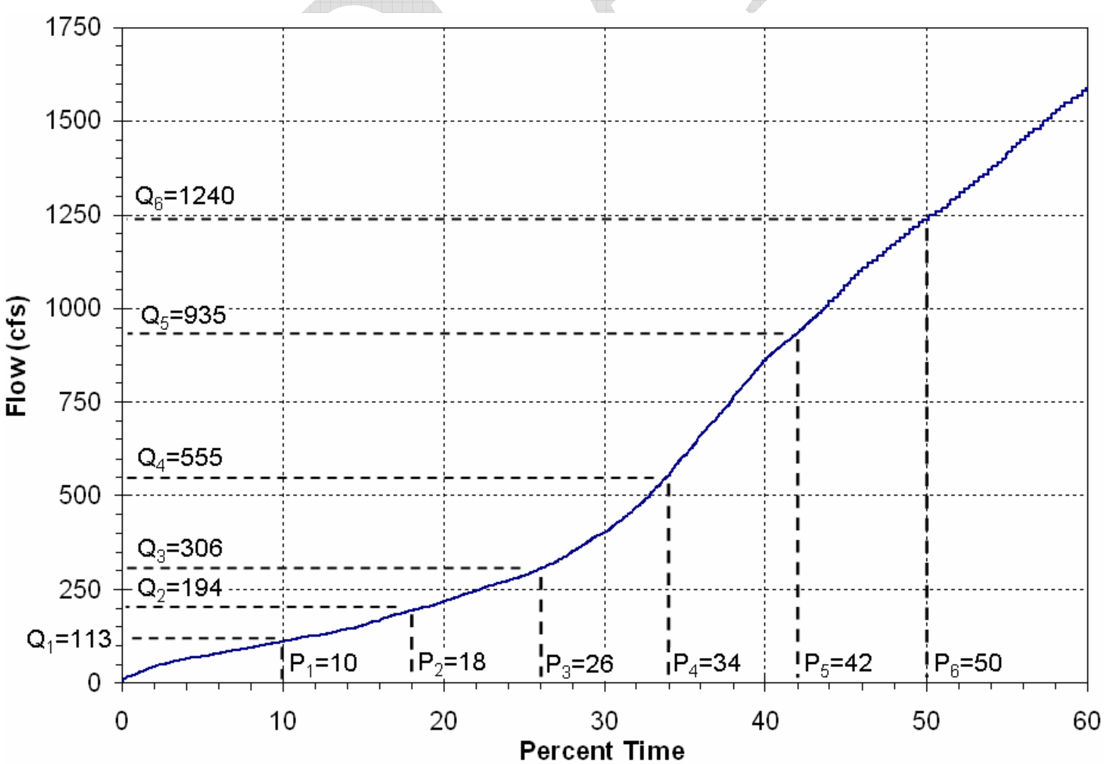

Figure 5.2. Cumulative probability curve with flow rates suitable for habitat modeling.

A cumulative probability curve is obtained by plotting flow versus cumulative probability as shown in Figure 5.2. Inspection of the cumulative probability curve allows determination of suitable flow rates at which to develop hydraulic models for habitat modeling. Flow quantity is considered to be a limiting factor for habitat at low flow rates. At the median (50^{th} 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 10^{th} 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.

5.2 Hydraulic Evaluation

Hydraulic evaluation based on numerical modeling provides input for development of both overbank and base flow components. For overbank flow development, one-dimensional (1-D) hydraulic modeling provides water surface elevations to estimate the extent of inundation in riparian areas associated with various flow rates. Nislow et al. (2003) used such an approach to make a "spatially explicit assessment of hydrologic alteration." For base flow development, a two-dimensional (2-D) 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.

5.2.1 Choosing a Representative Reach

In most cases, it is impractical to monitor, analyze, and hydraulically model an 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 located to address a particular concern in a specific sub-basin; for instance, a reach may be located directly downstream of a proposed diversion.

The possible length of a study reach is limited by the hydraulic model which will be employed. The lower computing power required by a 1-D 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 2-D models limits their feasibility to smaller study areas such as an area extending across the normal channel and along the river for no more than a few miles. In practice, this is not a severe limitation as the purpose of the study also limits the required length of the study reach. For example, habitat studies, which employ 2-D hydraulic models, do not require study reaches of more than a mile or two in length.

The choice of study site length and boundary locations is influenced by many factors, including the requirements for accurate hydraulic modeling. For 1-D 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; USGS, 2001). These same minimum criteria are applicable to multi-dimensional 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 perturbation.

Upstream and downstream boundaries of the hydraulic model are chosen with the behavior of the numerical model in mind. Relatively straight sections with uncomplicated banks and bathymetry allow for better behavior and greater numerical stability of the numerical model at the boundaries. To satisfy these requirements, the modeled reach may extend outside of the boundaries of the area of interest. In this case, extraneous hydraulic model information will be removed from the study reach analysis.

5.2.2 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 is dependant upon the accuracy of the data that describe the bottom bathymetric boundary (Carter and Shankar, 1997; Lane et al., 1999). Furthermore, the scale at which knowledge of 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 flow relationship. Many instrument options exist for measuring river flow rate, including acoustic doppler current profilers (ADCP), portable acoustic doppler velocity meters, electromagnetic velocity measurement devices, and mechanical velocity measurement devices. For channels with maximum depth greater than 1.5 meters, a boat-mounted ADCP is used to measure flow. The ADCP 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 USGS flow measurement methods (Prasuhn 1987). In shallow conditions (depths less than 0.66 meters) where it is possible to wade across the river, hand-held devices are more practical than an ADCP for flow measurement.

In order to verify 2-D 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 USGS gauging stations. Flow statistics calculated using historical gauging 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 gauging station, additional analysis will be performed as described in 5.1.1.

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. Semi-permanent 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 1-D and 2-D model output.

Bathymetric data for 1-D 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 1-D hydraulic modeling, see Brunner (2002).

Bathymetric data for 2-D models will be collected at very high spatial resolution using a boat-mounted differential GPS linked to a depth sounder. Since quantification of the spatial variability of habitat utilization is the objective of habitat flow studies, sufficient data must be collected to describe the causes of spatial variation in flow. Dominant bedforms, 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. Additional bed and bank elevation data to describe the cross-section above the median flow water line may be collected, if necessary, using traditional surveying or other techniques. See Appendix 5A for a detailed discussion of the data collection methodology for 2-D hydraulic modeling.

Combining flow rate data with water surface elevation data, a rating curve for the study reach will be developed. Such a curve is used to develop hydraulic models for flow rates where field data are not available. Traditionally, a rating curve is developed by measuring a high, medium, and low flow and applying those flows to a logarithmic regression. However, while a logarithmic regression may generally describe the water surface elevation versus flow rate relationship over a wide range of flows, the relationship may not be adequate to describe the small range of below-median flows that are of primary interest in a habitat flow study. Alternative linear or polynomial regression analyses may be employed that more accurately describe the observed system behavior at these flows. Habitat study site ratings should be compared to USGS ratings of sites that exhibit similar low-flow cross sections in the vicinity of the study reach. If significant discrepancies exist between the study reach rating and the USGS rating, additional data should be collected to improve the rating at the study reach.

5.2.3 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 non-uniformities 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. Multi-dimensional hydraulic models (of both two and three dimensions) are capable of resolving depth and velocity at many points in a cross section. One-dimenstional models are generally capable of providing water surface elevation data suitable for evaluating inundation of riparian areas during overbank flows. A 2-D hydraulic model has 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 are often used for water quality and over-banking flood flow models. Regulatory water quality models in Texas traditionally rely upon 1-D hydraulic advection models to determine constituent transport. Modeling of flood-flow water surface profiles and over-banking stage can also be performed with a 1-D model (such as HEC-RAS, WSP2, or MIKE11) in situations where disparate cross-sectional bathymetry information of the flood plain is available and where the modeled channel length far exceeds the channel width.

Until the mid-1990s, 1-D hydraulic models were used almost exclusively to model channel hydraulics for habitat flow studies. Such models require relatively little computational power and their numerical basis is less difficult to understand relative to multi-dimensional models. However, since most rivers have spatially complex hydraulic habitat, including across-channel velocity variations, many investigators have found 2-D models more suitable for habitat flow studies (Leclerc et al., 1995; Moyle et al., 1998; Railsback, 1999; Crowder and Diplas, 2000).

Discussion of HEC-RAS

There are a number of 1-D hydraulic models that may be appropriate for modeling inundation of riparian areas (e.g., HEC-RAS, WSP2, MIKE11, etc.). HEC-RAS has been chosen for TIFP overbank flow studies for several reasons. The HEC-RAS code is well-known and extensive training and documentation is available for this software (Annear et al., 2004). Additionally, it has been used with success for similar studies in other states (Nislow et al., 2003; Philip Williams and Associates, 2003). 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 flood plain management applications. (Additional information on HEC-RAS can be found in Brunner (2002) and Annear et al. (2004)).

Multi-dimensional hydraulic modeling

Multi-dimensional hydraulic models offer a number of features that make them favorable for application to habitat studies. They quantify lateral (across the channel) circulation patterns, velocity variation, and water surface elevation variation that cannot be quantified with 1-D models. Additionally, complicated river structures such as islands, cutoffs, backwaters, and debris can be incorporated into multi-dimensional models (Bates et al., 1997). Multi-dimensional models produce a spatially-explicit representation of hydraulic habitat offering expanded options for instream habitat analysis (Bovee, 1996; Hardy, 1998).

Both 2-D and three-dimensional (3-D) hydraulic models are available for use in studies of habitat during base flow conditions. Two-dimensional models historically utilized for river studies are depth-averaged so only horizontal variations in flow are simulated. Electro-fishing and other biological data collection techniques allow development of hydraulic habitat descriptions in terms of average column velocity, a good match for 2-D 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 3-D models but hydraulic habitat requirements are seldom described in this manner. 3-D models may be applied if strong vertical velocity gradients exist within a study reach or if knowledge of 3-D flow variation would improve the analysis of habitat availability. However, in most cases, a 2-D model will suffice.

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

<u>*Governing equations*</u>

Multi-dimensional 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 decomposition of the general modeling formulations is not presented here because it is presented in many manuscripts, texts, and refereed literature (see King et al., 1975; King, 1982; USACE, 1993; Leclerc et al., 1995; Walters, 1995; Finnie et al., 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 method 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 siutations in which large vertical velocities are present. With such limitations in mind, a model can be chosen to adequately describe 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 (i.e., no surface freezing and no saline tidal water). When considering overall channel hydraulics, the horizontal velocity gradients are more important than vertical gradients, allowing a depth-averaged (2-D) model implementing the RANS equations to be used (Leclerc et al., 1995; Vadas and Orth, 1998; Lane et al., 1999; Crowder and Diplas, 2000). However, 2-D depth-averaged models are less applicable where 3-D flow effects dominate, such as in the immediate vicinity (within centimeters) of large woody debris (LWD). Unfortunately, the extremely small grid scale required to address these types of problems limits the usefulness of applying 3-D models. Sub-grid scale turbulence modeling near LWD has been proposed (Hodges et al., 2003) and may make 3-D models more useful in the future.

An additional limitation to the application of most 2-D and some 3-D hydraulic models is presented by the presence of steep bed gradients (slopes greater than 20%) 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 (applies to most 2-D and some 3-D 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 natural system. Quantification of the error introduced by slope smoothing is difficult. Fortunately, these conditions do not occur frequently in the rivers of Texas.

Solution methods

Models reliant 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 utilized 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 et al., 1995; Mathews and Tallent, 1996; Austin and Wentzel, 2001; Austin et al., 2003; Osting et al., 2003). 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 (i.e., 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 instance, 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, flow obstructions, etc.) 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 will 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% (Donnell et al., 2001).

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 et al., 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 two and five square meters. 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 et al., 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, accurate description of 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 is a source of error because the traditional interpolation techniques such as inverse distance weighted (IDW), Thiessen polygon, cubic spline, and 2-D kriging do not take into account the known shape of a river channel (i.e., 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 since the proportion of anisotropy changes with changing flow direction.

To address this problem, the Mesh Elevating and Bathymetry Adjusting Algorithm was developed by TWDB and is used for assigning elevation 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 plan form by defining distance along the flow path and from the centerline. Rectangular search areas are defined for each node that weights the node (interpolate) 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 weighted (IDW) algorithm is employed to calculate the weighted average of the subset of scatter points (Franke, 1982).

Substrate, roughness, and moving beds

Multi-dimensional 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 1-D calculations of flow for an entire cross section (Prasuhn, 1987; Arcement and Schneider, 1989). The body force calculation is, however, still applicable in multi-dimensional models because it models the friction force at the bottom boundary and the turbulence in the water column (just like it does in the 1-D equations), the specified roughness applies over the entire domain of influence (the entire volume for which the calculation is being made), and no hard and fast rules exist for roughness coefficients in either one or multiple dimensions. A numerical estimate of roughness in 1-D may be slightly different than the estimate of roughness in 2-D for the same system (say, 10 percent difference), but the actual value is not 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 sub-grid-scale effects are not resolvable 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. Sub-grid-scale turbulence modeling is discussed elsewhere in this document with respect to large woody debris, but its application is equally useful for obstructions.

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 3-D model that couples hydraulics with sediment transport will be required.

Objects such as LWD 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 roughness coefficient (Manning's n) 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 ADCP 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 should include 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 2-D 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, ADCP cross-sectional current profiles can be measured at the same spacing. For 3-D models, vertical velocity profiles should also be measured at the same spacing.

Discussion of RMA-2

There are a number of multi-dimensional hydraulic models that may be appropriate for modeling habitat (e.g., RMA-2, FESWMS, CCHE2D, RMA-10, CH3D-WES, EFDC). Some hydraulic models have been designed specifically for fish habitat studies (such as River2D, HYDROSIM, and SSIIM2D) but have not been used by TWDB because of limited availability, array size limitations, or lack of mesh development tools. RMA-2 has been the model selected by TWDB for several recent habitat flow studies for several reasons (Mathews and Tallent, 1996; Austin et al., 2003; Osting et al., 2003). The RMA-2 code is well known and has been used with success by others (Deering, 1990; King, 1992; Finnie et al., 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 CITE). Brigham Young University's Surface Water Modeling System (SMS) software for mesh generation and visualization supports RMA-2 (EMSI, 2005). Most importantly, RMA-2 resolves flow features to a scale that is relevant to habitat studies. As computing power increases or if other models become available that 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 models.

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 the Manning or Chezy equation. Eddy viscosity coefficients are used to model turbulence characteristics. The code was originally developed in 1973 for US Army Corps of Engineers (USACE), with subsequent enhancements made by Resource Management Associates and USACE Waterways Experiment Station (Freeman, 1992; Donnell et al., 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 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 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 includes absolute fluid viscosity, Reynolds stresses, and some simplifying assumptions constructed to allow for solution of 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 et al., (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 Pa-s and also that the cell Peclet number should be between 15 and 40 (Donnell et al., 2001). Richards (1990) presents a model where the best replication of flow separation is achieved when 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 Pa-s when using small cells (< 5 meters 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 et al. (2001).

While 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 sub-critical flow problems in reaches without steep local bed slopes. If situations violating these conditions are encountered, another, more suitable hydraulic model will be used.

5.2.4 Special Problem: Large Woody Debris

Evaluation of habitat in rivers with extensive LWD is problematic. While the importance of LWD for certain fish species has been clearly demonstrated (Angermeier and Karr, 1984; Benke et al., 1985; Lobb and Orth, 1991), the large- and small-scale effects of LWD on flow and local velocity are particularly difficult to measure and model. In terms of hydraulics, there are four major issues (Hodges, 2002):

1. The scale of LWD is generally many times smaller than the resolvable flow scales in a typical hydraulic model of a river.
2. The flow effects of LWD are inherently 3-D, while hydraulic models currently used for habitat flow studies are typically either 1-D or 2-D.
3. Flow effects around LWD vary with depth of submergence.
4. LWD is fundamentally ephemeral, requiring either continuous field surveying, acceptance of a “snapshot” in time, or a model that predicts the collection/removal of LWD as a function of river discharge through time.

Whereas there have been considerable advances in the understanding of the ecological function of LWD in Texas (Bao and Mathews, 1991; Mathews and Bao, 1991; Mathews and Tallent, 1996; Mathews and Tallent, 1997), there remains much to be determined with respect to the hydraulic function of LWD.

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6. 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 (e.g., dissolved oxygen, temperature regimes, turbidity) will be of primary concern in a particular reach of river. Habitat considerations will include maintaining adequate flows so that key habitats (e.g., riffles) are not dewatered or reduced to unsuitable (deadly) conditions for lotic-adapted species (such as mussels, riffle-dwelling fishes and invertebrates) or imperiled species.

Base flow recommendations will rely primarily on habitat criteria derived from biological data to assess instream habitat (quantity, quality, and diversity) relative to stream flow. These habitat models provide a means to identify a range of flows that provides suitable habitat conditions and allows for quantitative comparisons of different flow scenarios (e.g., 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 development of the high flow pulses component of the flow regime. Development of overbanking flow recommendations will include evaluation and modeling of riparian systems and linkages between aquatic biota (e.g., floodplain spawning fishes) and active floodplain and channel processes. The historical hydrology for these two flow components (high flow pulses and overbanking flows) will largely determine magnitudes, 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 existing information (rather than instream habitat modeling) will be most effective for development of these flows.

6.1 Introduction

A central focus of instream flow studies is to relate the biology of a lotic system to its flow regime since hydrology plays a substantial role in determining the composition, distribution, and diversity of aquatic communities (Bovee et al. 1998; Annear et al. 2004). Indeed, riverine biota has evolved life history strategies that correspond to natural flow regimes. Information to address flow needs in key habitats (e.g., shallow-water habitats) and during critical time periods (e.g., spawning and rearing) is an essential element of these 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 provide insight in the integration element. Fish are advantageous target organisms because they are relatively easy to identify; they use a wide array of habitats including flow-sensitive habitats; they offer a wide range of life histories many of which are tied to flow dynamics; they are generally well studied relative to other aquatic taxa; they are a good integrator of overall health of the system; and they are also of 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). 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 responds (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 et al. 2004). Many riverine fishes time migration, spawning, and other activities to seasonal changes in flow regimes (see Stalnaker et al. 1996) in addition to their usual flow requirements. Flow regimes also influence physical and chemical conditions in rivers and streams, which in turn influence biological processes. For example, flushing flows transport accumulated fine sediments that may impair 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 et al. 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 whose structure and functions are dependent upon flow regimes (NRC 2002). They are normally 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 NRC (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 stream banks. 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 et. al. 1991). It is estimated that 80% 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 process such as meandering (Busch and Scott 1995). Studies by Busch et al. (1992) of plant water uptake in floodplain ecosystems indicated that maintenance of cottonwood and willow populations depends on groundwater moisture sources, which, in turn, are closely linked to instream flows. Busch and Scott (1995) concluded that the establishment and maintenance of riparian plant communities are a function of the interplay among surface water dynamics, groundwater, and river channel processes. They maintained 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, the construction of dams, 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 the result of dams typically include the complete inundation and subsequent elimination of riparian habitat upstream of dams, 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 (Lytle and Merritt 2004).

6.2 Baseline Information

Baseline information is necessary to develop an understanding of the aquatic biology of each system in relationship to instream flows and to identify key physical, hydrologic, and chemical processes, and critical time periods. Needs include information on life history traits (e.g., spawning season and needs, foraging traits), environmental requirements (e.g., habitat, temperature, dissolved oxygen), species distributions, community composition, and connectivity considerations.

Existing information will be compiled from reports by state agencies (TPWD, TCEQ, TWDB or predecessor agencies; state agency reports from Louisiana, Oklahoma and New Mexico will also be obtained as appropriate); federal agencies (U. S. Geological Survey, U. S. Fish and Wildlife Service, U. S. Bureau of Reclamation, and U. S. Army Corps of Engineers); journal articles; reports from river authorities and water districts (including Clean Rivers Program Assessments and reports written by contractors); university studies and museum records; and 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. Review and analysis of the collected information will provide a summary of the state of knowledge, facilitate development of conceptual models, and identify areas that need further attention. Baseline field surveys (see 6.2.2 for example) will be conducted to address data gaps and identify trends in assemblage dynamics. Further, these baseline surveys will facilitate the development of study goals, objectives, and indicators, sampling strategies, identification of taxa of interest, and delineation of study boundaries and intensive study areas.

6.2.1 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,
- Run/Glide - low slope, smooth, unbroken surface,
- Riffle - moderate slope, broken surface,
- Rapid - moderate to high slope, very turbulent (e.g. boulder field), and
- 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 (e.g., a unique outcrop) and substrate composition will be taken. Measurements of current velocity and depth will be taken to facilitate development of objective criteria for defining meshohabitat 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 median conditions when 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 calls.

6.2.2 Fish Surveys

For each study reach, identifiable mesohabitats will be sampled for fish using the most appropriate gear (e.g., seines, electrofishers). Reach lengths will be 40 times the mean wetted width of the stream up a distance of 1000 m. Physical measurements will be made in association with each sampling event (e.g., each seine haul) and will include current velocity, depth, substrate composition and embeddedness, instream cover (large woody debris, boulders, undercut banks, macrophytes, velocity shelters, etc.), 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 6.3.3), provide data on baseline conditions for monitoring and verification, and allow appropriate biological indices to be calculated. Released fish will be identified, measured, photo-documented, and examined for disease and other anomalies. Voucher specimens will be preserved in 10% 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 (e.g., pools, fast runs). An attempt will be made to collect all shocked fish; special effort will be exerted to collect fishes that may be rolling on the bottom. Electrofishing will pause when a particular habitat has been thoroughly sampled so that fish collected can be enumerated. 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 (e.g., riffles, shallow runs). Seines placed downstream of the backpack crew can be used to assist in fish collection, if necessary. 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.

Seining (at least 10 effective seine hauls) will be conducted in various habitats using a variety of seines and seining techniques (e.g., riffles kicks) in order to complement shocking efforts. Examples of commonly used seines include a 9.1 m x 1.8 m x 7.6 cm (30’ x 6’ x 1/4”) mesh seine for sampling pools and open runs and a 4.6 m x 1.8 m x 5.7 cm (15’ x 6’ x 3/16”) 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.

6.2.3 Aquatic Invertebrate Surveys

For each study reach, three types of samples will be collected: kick-net, woody debris (snag), and hand-picked. For benthic samples, nine kick-net samples will be taken for 20-seconds each using a large-tapered kick net (600 µm-mesh, 330 x 508 mm frame size, or similar net). Sampling will occur over an area approximately 1 meter by 0.5 meter directly in front of the collecting net. Three samples each will be collected from each major habitat present (i.e., 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 stream current will carry dislodged invertebrates into the collection net. For pool samples, where current 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 µm or less) to eliminate fine silt and sand. Remainders of the bulk benthic samples will be individually preserved in at least 70% isopropyl alcohol. The preservative will be replaced with fresh isopropyl alcohol after 12 hours to insure proper preservation.

Woody debris will be collected in amounts sufficient to fill a one-gallon collection jar and then preserved with at least 70% isopropyl alcohol. Woody debris will be collected from throughout the study reach and should include well-seasoned and highly-reticulated woody debris with irregular or rough surfaces. Green wood or very small diameter (<2 cm) pieces should be avoided.

Hand-collected sampling consists of collecting miscellaneous aquatic invertebrates from stones, woody debris, and other substrates as appropriate. Special effort should be made to collect a wide variety of immature mayflies to aid in the identification of specimens collected in benthic samples. Specimens collected will be preserved in at least 70% 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 µm 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 found being stored in individual vials and preserved with at least 70% isopropyl alcohol. Specimen vials will be labeled to show collection location, type 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 µm 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% isopropyl alcohol. Snag material will be measured volumetrically (cm^3) 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 (e.g., Pennak 1989; Merritt and Cummins 1996). For sample analysis, the following metrics (TNRCC 1999) will be calculated, as appropriate, on data collected using the aforementioned collection methods:

a. Taxa richness,
b. Ephemeroptera-Plecoptera-Trichoptera (EPT) ratio,
c. Ratio of EPT and Chironomidae abundances,
d. Percentage Cheumatopsyche of total Trichoptera,
e. Percentage contribution of dominant taxon,
f. Percentage exotic species,
g. Ratio of scraper and filtering collector functional feeding groups,
h. Benthic densities: number of specimens per square meter, and
i. Snag samples: number of specimens per cubic centimeter.

6.2.4 Riparian Area Surveys

Hardwood bottomlands and other wetland systems (e.g., oxbows) are important riparian habitat types, the evaluation of which warrants detailed assessment. Existing information on 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 (i.e., 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, the identification and distribution of 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 needs. The methodology to address these factors in determining riparian area distribution follows.

Remote Sensing: While 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 orthophotoquads from 1995 and 2004 will then be assembled. Vegetation and landscape features will be digitized from the digital orthophotoquads and converted into shape file layers using ArcGIS. These shape files will be overlaid on the ETM+ base map.

Topography: USGS topography data (e.g., DEMs, TINs) 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 as a component of the hydrologic requirements for maintaining healthy riparian ecosystem model (see *Determining Hydrologic Flow Requirements Necessary for Maintaining Riparian Areas*).

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 as native indicators may no longer be present. Therefore, soil characteristics derived from 1:24,000 Soil Survey Geographic Database (SSURGO) data 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 USGS 1:24,000 data will be assembled and correlated to the soils, topography, and riparian vegetation classification layer on the ETM+ 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, nutrient cycling, etc.

Determining Hydrologic Flow Requirements Necessary for Maintaining Riparian Areas

When determining flow requirements for the maintenance of 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 overbanking flow requirements of riparian ecosystems has yet to be developed. Therefore, a model will be developed using three components: USGS topography data, USGS 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 timeframe of the dominant native vegetation type found within the riparian plant communities (or linked to life histories of other taxa such as fishes that utilize riparian areas) to determine the duration, magnitude, and timing recommendations of overbanking flow events.

Connectivity of Riparian Ecosystems

To further elaborate the importance of hydrology to the ecological integrity of riparian systems, Petts and Kennedy (2005) maintain 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. They cite 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, Petts and Kennedy (2005) develop a model (Figure 6.1) that delineates an indicator variable from hydrological data series. This model defines the space of interaction between non-atmospheric water and substrate as a gradient of probability of inundation of both superficial area (FZ) and unsaturated groundwater zone (UZ). Swamp zones occur when the UZ overlaps the FZ. The transitional water table distance (TWD), 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.

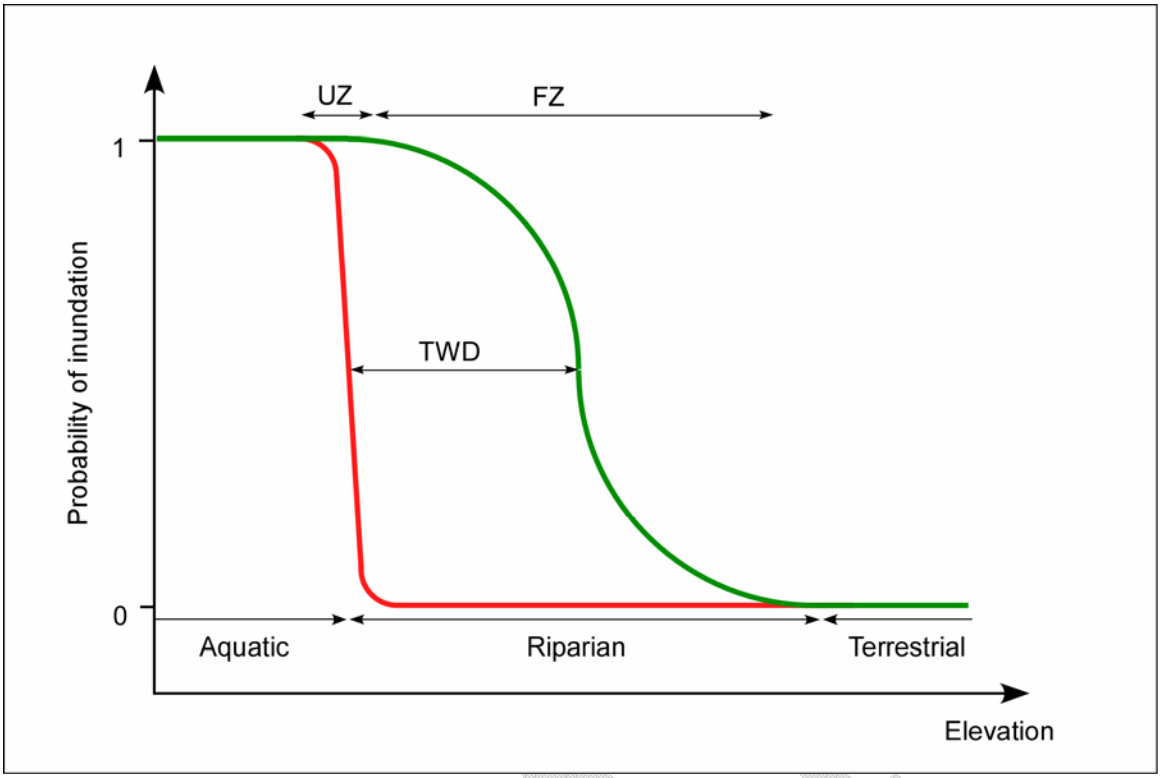

Figure 6.1. Hydrological representation of the riparian zone as a sum of transitional gradients. The red line depicts the long-period probability of inundation by groundwater as a function of elevation. The green line represents the long-period probability of inundation by groundwater as a function of river water level. The unsaturated zone of the water table is represented by UZ, while the flooded zone is represented by FZ. The transitional water table distance (TWD) depicts 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% confidence intervals for the two cumulative distribution functions. Transition curves can be asymmetric. Modified from Petts and Kennedy (2005).

6.3 Instream Habitat

Most instream flow studies model habitat availability in response to discharge with the basic assumption being that physical and hydraulic variables determine the spatial distribution of aquatic organisms (Bovee et al. 1998; Annear et al. 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 time and resource intensive. Resource limitations and time constraints (studies are expected to be completed in 3 to 5 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 uncertainty in instream flow management and restoration (Castleberry et al. 1996; see Richter et al. 1997). However, given that water rights in Texas are granted in perpetuity, opportunities for adaptive management are very limited.

Two complementary approaches to assessment of 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.

6.3.1 Quantity and Quality of Instream Microhabitat

One focus of the biological study element is to assess the quantity and quality of instream microhabitat used by lotic organisms and relate that utilization to stream flow. 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; and
- 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 at stream flows that make available the full complement of potential habitats thereby providing choice to biota. Food availability, competition, and predation can influence habitat selection and may need to be addressed (Power 1984; Orth 1987). Sampling at a normal range of flow may minimize these influences and provide choice in habitat selection.
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 during the study design phase and will be based on literature review and empirical information collected during baseline 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 et al. 1998). Other variables may need to be addressed depending on taxa. For example, near-bed hydraulics (e.g., shear stress) has been used to relate macroinvertebrate and mussel distributions, and in some cases densities, to microhabitat conditions (Gore et al. 2001; Hardison and Layzer 2001).

Many approaches for collecting microhabitat utilization data in a quantitative manner have been developed and used in instream flow assessments. However, given the diversity in characteristics among rivers (biology, habitat, etc.), 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-m^2) 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 et al. 2001). Within each cell, biota is sampled and habitat characterized. Bio-grids are used for sampling in shallow habitats (e.g., 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, pre-positioned area electrofishers, and various seines. With the exception of boat electrofishing, these techniques are limited to relatively shallow habitats (i.e., about 1-m deep); high current velocities may also preclude sampling in some locations.

Collection of macroinvertebrate habitat-utilization data attempts to be more quantititative than baseline 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 et al. (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 (e.g., 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 et al. 2004). For example, many darter species prefer high velocity, shallow habitat 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, cobble, etc.) are occupied by smaller substrates like silt and sand,
- instream cover, such as woody debris, macrophytes, velocity shelters formed by objects and substrates, undercut banks, etc.,

- mesohabitat type (see 6.2.1),
- other hydraulic variables (e.g., shear stress) as required by study design, and
- 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 accurately characterize microhabitat conditions.

In some cases, in may be necessary to identify target species that have key habitat requirements (e.g., shallow habitat for spawning) and critical time periods (e.g., limited spawning season). Species that utilize key habitats may be of most importance because these habitats are substantially affected by reductions in stream flows. For example, many darter species in Texas solely use riffle habitats, which, as flows decline, become exposed or unsuitable (i.e., 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 stream flow 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 et al. 2001). Utilization criteria are calculated based on relative proportions of habitat used by target species or guilds while preference criteria account for the availability of habitat conditions. The concept of nonparametric tolerance limits has been applied to development of 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 while 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 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 needs 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 needs thereby avoiding stochastic factors (biotic and abiotic) that influence individual species (Vadas and Orth 2000). Perhaps most importantly, mesohabitats can be defined from 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 (e.g., Aadland 1993) and multivariate (e.g., Vadas and Orth 2000) methods many of which are readily available in statistical software packages (e.g., 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 et al. 1999 for discussion of transferability of suitability criteria). Peterson and Rabeni (1995) advocate use of fish guilds for stream fish community studies and also indicate use of such would increase the cost efficiency of a study by reducing sampling effort while obtaining a reasonable level of precision. Further, it may also be necessary to generate habitat suitability criteria for individual target species, especially those with specialized habitat requirements (e.g., fluvial habitat specialists) or specific environmental needs at critical times. Imperiled species may also receive separate attention. For instance, Mosier and Ray (1992) made recommendations for flow regimes in the Colorado River, but also included provisions for increased flows to facilitate spawning conditions for *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 9.2.1 Physical Habitat Model.

Develop habitat time series

Habitat time series will be produced using habitat-discharge relationships and hydrologic time series (Bovee et al. 1998). A necessary component of this analysis is hydrologic time series at temporal scales (e.g., daily, monthly) appropriate for the taxa of interest. Hydrologic time series (see Chapter 5 Hydrology and Hydraulics) 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 et al. 1996). The timing, duration, and amount of habitat can provide insight into potential habitat bottlenecks (Bovee et al. 1994).

6.3.2 Habitat Heterogeneity

A complementary assessment will relate habitat heterogeneity with stream flow. 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 et al. 1993; Bunn and Arthington 2002; Robinson et al. 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 et al. 2002). Lotic ecologists are integrating the themes of landscape ecology into riverine ecology (e.g., Fausch et al. 2002; Ward et al. 2002; Wiens 2002) and this may have important implications in the assessment of instream flow needs.

Spatially-explicit habitat models, derived from GIS systems and 2-D 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 et al. 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 stream flow will be conducted. The first step is to classify instream habitat at an intermediate scale. Jowett (1993) used Froude number to distinguish pools and riffles. Vadas and Orth (1998) developed hydraulic criteria to classify mesohabitat types (riffles, runs, pools) in warmwater streams (<50 m 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 (e.g., shallow, margin habitat) based on biological criteria using fish (Bain and Knight 1996; Bowen et al. 1998; Freeman et al. 2001) or benthic communities (Pardo and Armitage 1997). NRC (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 apprpoach since it is tied to the use of mesohabitats by lotic organisms. However, the specific approach utilized in each basin study will be dependent upon the habitat characteristics of the river basin and biological communities. The second step is to model how mesohabitat changes with stream flow using a spatially explicit habitat model (see Chapter 9). The third step is to characterize the resultant habitat mosaic, at each flow level, using landscape metrics (patch size, diversity, etc). Bowen et al. (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.

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7. Physical Processes

Streams and rivers transport not only water, but also sediment. Water carries sand, silt, 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 dependant. As a result, physical processes play an important role in the development and maintenance of 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 required. Management of the Trinity River in northern California illustrates this point. As described by Trush et al. (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 et al. (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 TIFP, 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 reworking the shape and form of channel banks and bed forms. However, during studies to develop base flow requirements, an assessment of channel bedform and banks will assist biologists identifying important physical habitats. Investigation of 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 the development and maintenance of 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). Although smaller in magnitude than overbank flows, high pulse flows 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 the development of physical habitats. These processes may include scouring of pools, sorting of sediments, and creation of specific bedforms or specialized channel habitats such as undercut banks. Sediment budgets describing the sources and deposition of sediment in the river system will be developed. These budgets are used to identify sediment limitations or excesses that may impact the ability to achieve desired outcomes. The ability of current and alternative sediment and hydrologic regimes to adjust channel features can then be assessed. Recommended values for high flow pulses will be developed, with consideration of seasonality, magnitude, frequency, duration, and rate of increase and fall.

Overbank flows provide critical functions in support of river ecosystems. These include development and maintenance of floodplain habitats, provision of nutrients and sediments to riparian areas, transport of organic debris to the channel, and prevention of 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 5.2) and results of riparian area surveys (described in Section 6.2.4) may assist in developing appropriate overbank flow recommendations. Geomorphic assessment of overbank and high pulse flow behavior will also include analysis of 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 TIFP 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 will need to be tailored to the specific sub-basin being investigated. Secondly, the lack of baseline geomorphic data for Texas' rivers is problematic. Studies can describe current conditions by collecting data related to processes on each river. But without historical data, past conditions cannot be understood and the ability to accurately predict the future response of a river is reduced. To correct this situation, a monitoring program that collects geomorphic data for major rivers at least every five years is recommended.

7.1 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 that is 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 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 sediment discharge (Q_s) to stream discharge (Q) in terms of bed sediment particle size (D_{50}), bed 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. From Lane's equation, we can see 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 plan form, 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 20 to 50 years for a floodplain to regain a shape and form similar to its original. Lateral migration of the channel accounts for about 90% of the deposited sediments in a floodplain. Vertical accretion and the attachment of river islands to one bank or the other also help to build the flood plain.

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, as shown in Table 7.1.

Brussock, Brown, and Dixon (1985) found that in Texas, river-bed type varied along the length of rivers, from upstream to downstream location. They classified regions in Texas as mid-continental, eastern Coastal, or ephemeral and characterized the beds of rivers for each region. The mid-continental region has rivers which are gravel bedded in their extreme upstream areas, slowly change to sand bedded in their middle reaches, and whose lower reaches start out with sand beds and change to gravel beds. 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 mid-continental region, but small- and mid-sized streams are dry most of the year.

Table 7.1. Classification of river bed types (adapted from Knighton 1984).

Class	Type	Character
Non-Cohesive	Sand	Composed largely of sand-sized material. This size is transported over a large range of discharges. Called "mobile" or "live" bed.
	Gravel	Composed of gravel or small cobble that are 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.

The beds of rivers are typically permeable to water, which can flow into or out of the stream bed and banks depending on local conditions. Water accumulation or depletion can be determined by measurement of river discharge and groundwater level from wells near the channel. The increasing use of ground water creates a need for better understanding of river/groundwater exchanges in parts of the state.

7.2 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 et al. 1996; Friedman et al. 1998; Graf 1999; Brandt 2000; Graf 2001; Wohl 2004). As shown in Table 7.2, river segments can be classified according to the impact of human activities on their geomorphic processes.

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 7.3 lists possible changes in channel characteristics due to changes in flow and sediment discharge associated with such 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%. 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 7.3.

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).

Table 7.2. Geomorphic "Naturalness" classification of river segments (adapted from Graf 1999).

Channel Type	Completely Natural	Essentially Natural	Partially Modified	Substantially Modified	Mostly Modified	Essentially Artificial	Completely Artificial
% Channel Change	0%	<10%	<10%	10 to 50%	50 to 90%	90 to100%	100%
Pattern, X-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

Table 7.3. Potential alterations in channel characteristics due to changes in river discharge and sediment discharge (from Petts 1979).

Change in Transport Variables	Water Discharge	+	-			+	-	+	-		-
	Sediment Bed Load Discharge			+	-	+	-	-	+	-	-
Potential Alteration in Channel Characteristics	Width	+	-	+	-	+	-	+ or -	+ or -	+ or -	-
	Depth	+	-	-	-	+ or -	+ or -	+	-	+	+ or -
	Width-to-Depth Ratio	+	-	+	-	+	-	+ or -	+ or -		
	Meander Wavelength	+	-	+	-	+	-	+ or -	+ or -		
	Bank Full Area									+	-
	Sinuosity			-	+	-	+	+	-	+	+ or -
	Channel Gradient	-	+	+	-	+ or -	+ or -	-	+	-	+ or -

Note: + and - indicate an increase or decrease, respectively, in a variable or characteristic. An empty cell indicates no change in the variable or characteristic.

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

Where, 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% (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 re-supplied by the watershed, banks, or channel of the river.

The only fail-safe way to determine 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 on 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 effect 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 available in the office and include geology, soils, land use, hydrology, plan form 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. Table 7.4 lists aspects of a geomorphic analysis of direct interest to the management of river systems.

Table 7.4. Aspects of fluvial geomorphology of direct interest to river management.

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

7.3 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 orthophotos, stream gauge records, and other data sources that illustrate changes the river has undergone from the past to its present condition. 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 change. Their sediment transport rates are related to their sediment supplies. 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 are dependent 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, for stable, sand-bedded rivers, the bed 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).

7.3.1 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 pre-disturbance conditions. For example, water diversion to the Milk River of Montana caused the meander migration rate to increase to 0.85 meters per year while the channel width increased by 5.5 meters (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.

7.3.2 Assess present channel adjustments

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

Plan form measurements

Plan form 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. Characteristics that can be measured and compared include:

Meander belt width is the distance between lines drawn tangential to the extreme limits of fully developed meanders.
Sinuosity is the stream length divided by the valley length.
Meander wavelength is 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. Measurements made from cross-sectional data include:

Base flow width is 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 is the mean depth during base flow conditions.
Base flow wetted perimeter is the wetted perimeter as measured during base flow conditions.
Channel depths of the 1, 2, 3, and 5-year floods are the depths of the channel during the **1-, 2-, 3-, and 5**-year return interval floods (the floods that occur, on average, every **1, 2, 3, and 5** years).
Channel widths of the 1-, 2-, 3-, and 5-year floods are the average widths during the **1-, 2-, 3-, and 5**-year floods. Note: The term "bank full" width is generally equated to channel width, but "bank full" is an ambiguous term, has several different definitions (Williams 1978), and is especially difficult to determine for some regulated rivers in Texas.
Channel wetted perimeter of the 1-, 2-, 3-, and 5-year floods are the wetted perimeters as measured during the **1-, 2-, 3-, and 5**-year floods.
Bank height is the distance from the top of the bank to the bottom.
Bank slope angle is 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 is 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 under story 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 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 to evaluate channel pattern depending on the river bed material. Bedform configurations for sand-bedded streams are defined by the forms created in the bed. These include ripples, dunes, anti-dunes, and flat beds. These features are formed by different shear stresses acting on the cohesion-less 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 bedforms are common in sand-bedded rivers, the mechanisms that cause their formation in natural streams are poorly understood.

Bedform configurations in gravel-bedded rivers are defined by across channel features called "pools and riffles." At normal flow levels, pools generally have a slower velocity with deeper water depth while 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 bedform measurements that can be taken for a gravel bed stream include:

Riffle length is the distance between the top and bottom of the riffle.
Riffle gradient is the change in elevation of the channel bed from the top to the bottom of the riffle divided by the riffle length.
Inter-riffle length is the longitudinal distance between center points of successive riffles, measured along the centerline of the channel.
Inter-riffle gradient is the change in elevation of the channel bed between the beginnings of successive riffles divided by the inter-riffle length.

Inter-pool length is the longitudinal distance between the deepest points of successive pools, measured along the centerline of the channel.
Inter-pool gradient is 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. Cobble-bedded streams contain bed material with mean diameters between 64 to 256 millimeters. Gravel-bedded streams have material between 2 to 64 millimeters in mean diameter while sand-bedded streams contain bed material composed of sediment with diameters less than 2 millimeters. 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 while 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.

7.4 Sediment Budgets

Sediment particles are created as erosional products of rocks 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 hillslope-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.

The movement of sediment particles can be evaluated 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 bedload (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 hillslope. 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 response or a comparison of the responses of similar landforms under different conditions. There are several methods to conduct 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 scale, and available resources and data. For a more complete description of sediment budget studies, see Reid and Dunne (1996). TIFP sediment budget studies 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. Calculation of incipient motion can be a very complex problem and there are several methods from which to choose. For TIFP studies, the choice to conduct an incipient-motion study and the selection of methodology will be decided on a reach-by-reach basis.

7.5 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. 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 watershed, province, valley, channel reach, or morphological unit (see Rosgen 1996). The NRC (2005) suggested that a geomorphic classification scheme for water allocation studies should have the following features:

1. Be hierarchical in its structure,
2. Be physically based,
3. Include the floodplain,
4. Relate channel to physiographic and hydrologic setting, and
5. Contain channel morphology such as plan form, 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 et al. (2003) reviewed 21 classification schemes and mentioned several newer schemes that they did not evaluate, including Raven et al. (1997) and Brierly and Fryirs (2000). As comprehensive as their review was, there are even more schemes available, including Rowntree and Wadeson (1998) and Parrott et al. (1989).

As many river classification schemes as there are to choose from, very few include all of the features recommended by the NRC (2005). For example, the first recommended feature for a scheme is a hierarchical nature. To do so, large map units of the classification scheme must interlock with constraints of the small-scale map units. Of the schemes reviewed by Kondolf et al. (2003), only two, Bethemont et al. (1996) and Frissell et al. (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 et al. (1996) fails to evaluate physical features of the substrate, sediment load, and morphodynamic adjustments. Frissell et al. (1986) meets the first and second criteria of the NRC, but was developed for small, mountain streams.

Brierly 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 NRC. An assessment algorithm, called River Styles^{TM}, based on this framework is currently being used for environmental studies in Australia. For the remainder of this document, the lower case term ‘river styles’ (or the abbreviation RS) will be used to reference the basic logic and scientific approach described by Brierly and Fryirs (2005).

7.5.1 River styles framework

The river styles (RS) framework is a scaled hierarchy in both time and space which organizes map units and information about a river system into a structured database. RS 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 prediction of expected future changes such as those due to human influence or climate-driven effects.

The RS 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. As shown in Figure 7.1, these categories have different spatial scales and are related hierarchically. The geomorphic variables related to a mapping unit are related to the evolutionary time during which changes in geomorphic conditions within that unit occur.

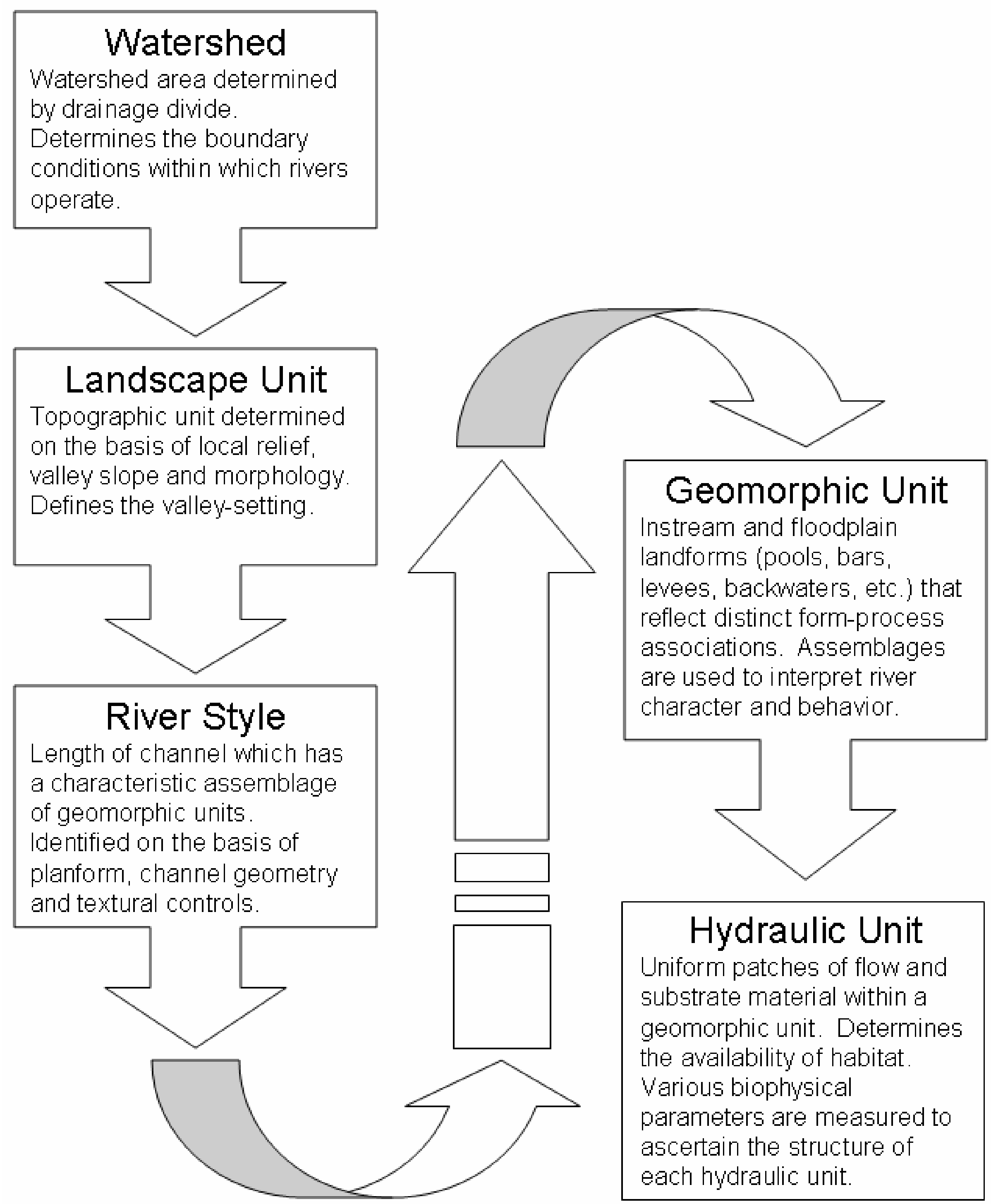

Figure 7.1. Hierarchical relationship of river style mapping categories (from Brierly and Fryirs 2005).

Landscape characteristics

In an evaluation of landscape characteristics, RS divides these characteristics into control and response variables (described in Section 7.2). 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, climate and generalized land use

Geology and climate are broad-brush 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 on this new map, the map units that the river touches or crosses can be observed. Each of these touched or crossed areas can be delineated as a different zone of the river.

USSCS (1982) provides a map of 20 land-resource areas within the State of Texas which may be further subdivided into smaller Common Resource Areas (NRCS 2006). These areas are characterized by a grouping of 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.

Hydrology and watershed characteristics

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” is an important feature of Texas rivers. The Baker (1977) flash flood magnitude index (FFMI), which is the standard deviation of the logarithms of annual maximum stream flow, varies from about 0.19 for the Calcasieu River in Louisiana to 0.9 for the West Nueces River, near Bracketville, Texas. This index should be calculated to provide a way of comparing Texas rivers. Other seasonal differences in flow patterns can also be used to separate river zones.

Valley characteristics

Changes in valley characteristics such as valley shape, valley width, and location of the channel in the valley can be used to create classification units that are used to further subdivide a river channel system. A major part of this exercise is to delineate the various geomorphic units in the valley.

Responses to larger scales units

Channel features such as channel slope, sinuosity, and channel bed form are used to further classify channel reaches into smaller scale units. The major feature used in this classification is sinuosity as measured from aerial photographs or digital imagery. At an even 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.

Connectivity of river basin

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 RS 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 7.2. Although this river system is very simplified, the figure does show how the RS method classifies river segments based on significant geomorphic factors.

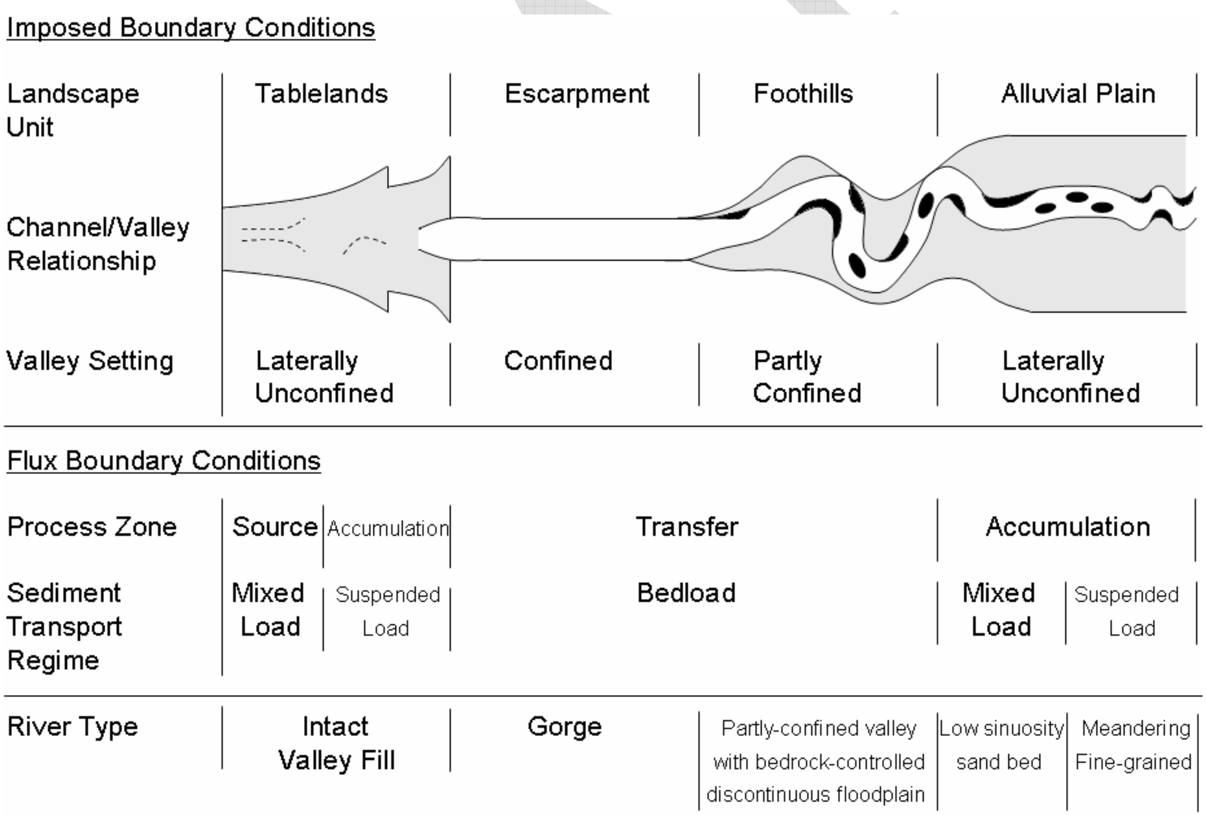

Figure 7.2. Example of longitudinal segmentation of a river system based on RS methodology (adapted from Brierly and Fryirs 2005).

River behavior

An important part of the RS framework is an analysis of the various flow levels that maintain a river's energy, ability to do work, and morphometric characteristics. Flow levels are primarily determined by climate (through rainfall), geology (through erosive nature of rocks and soil characteristics), vegetation, and human activities. Flows that have a significant impact on river behavior can be 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) and continue forward to today and into the future. During this time period, there have been changes in climate, vegetation, and river base levels. A river's response to these changes is related to the system's thresholds. If the changes pushed a river beyond a threshold value, the river will be actively seeking a new pattern of behavior. If the changes did 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. Direct, human-induced changes of greatest impact to Texas' rivers include:

1. **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.
2. **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.
3. **Sand and gravel removal** from the river bed and banks can affect processes by depleting the supply of sediment needed to dissipate the energy of the river.
4. **Removal of woody debris** from the channel, wetlands, and river corridor affects flood processes and habitat for wildlife along rivers.

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

1. **Forest removal** impacts the behavior of small watersheds causing them to produce more water and sediment. The increased sediment may alter the composition of various parts of the river system such as gravel bars.
2. **Urbanization** affects the soil's ability to absorb water, alters runoff timing, and increases flood magnitude.

3. **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.

Assess past channel history

What the river did in the past helps explain what it will do in the future. If the river had a high meandering 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 (e.g. 50 years), the process and rate of movement becomes clear. The following changes can be identified from historical data:

1. Land use pattern,
2. Channel plan form values (sinuosity, width),
3. Gradient and channel length, and
4. Bank erosion or protection.

Assess future condition of river system

Unfortunately, geomorphic baseline data are limited for most river segments in Texas. Without these data, prediction of a river's response to water diversions or dams is difficult. Some inferences can be made from historical aerial photographs or other sources. The Agencies are exploring the potential of using historical measurement data at USGS gauge 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.

For most rivers in Texas, however, the best that can be done is to observe trends in the geomorphic processes that can be measured under current conditions. This can be accomplished by sediment budget analysis and initiating a monitoring program that collects geomorphic process data every five years or less. With the collection of this information, the following principles can be used to guide interpretation of the system's response:

1. Evaluate the river's variability and capacity for change in its valley setting.
2. Identify the balance between erosional and depositional processes.
3. Interpret where the balance between input and resisting forces is proceeding over time.
4. Identify threshold conditions that lead to change.
5. Estimate how the river system may change with proposed flow regimes.

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8. Water Quality

Water quality concerns are linked to the concerns of the other disciplines whose role in the TIFP have been 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 TIFP 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 (DO) concentration 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. DO 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 (CWA) and the Texas Water Code Chapter 26, and demonstrates linkages between water quality and variable flow regimes. While 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 the water chemistry aspects.

8.1 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 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 modifications in both flow and water quality have occurred over the last 100 years in direct response to human activities. Spring flows have been reduced to provide water for agricultural irrigation, municipal needs, and industrial activities. 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. While some of these impacts are unavoidable consequences of human activities (i.e., loss of sediment transport through reservoirs), water quality impacts resulting from point source discharges and nonpoint source runoff are addressed through water quality management programs.

TCEQ has jurisdiction over the state's water quality programs, including adoption of surface water quality standards, enforcement of water quality rules, issuance of permits, and water quality planning (TWC Chapter 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 regulation of point source discharges and funding of remedies for nonpoint source pollution. TCEQ prepares the State of Texas Water Quality Inventory and submits the report to the USEPA biennially in even-numbered years pursuant to section 305(b) of the Clean Water Act. The most recent submission was prepared in 2004 (TCEQ 2004a). Additionally, TCEQ 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 URLs listed with each program.

8.2 Water Quality Programs in Texas

The CWA framework, implemented by TCEQ, 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.

8.2.1 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. The state of Texas uses a varying cycle of activities to manage water quality based on statutorily-determined timeframes. Steps in the cycle include:

- Establishing or revising water quality standards; determining appropriate aquatic life use designations
- Collecting data at routine, 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 (e.g., recreational, public water supply) are not met
- Implementing pollution control measures and monitoring the results

8.2.2 Surface Water Quality Standards

The Texas Surface Water Quality Standards (TAC 30 §307.7) fulfill state and federal requirements to:

- establish uses,
- set criteria to maintain the established uses, and
- establish an anti-degradation policy.

The rules establish numerical and narrative goals for water quality throughout the state and provide a basis on which TCEQ 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. Segment-specific uses and water quality criteria have been developed for 225 classified water quality segments representing 14,238 miles 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 (Table 8.1). Water quality standards have been adopted for all streams that have been identified as priority segments in the Programmatic Work Plan (Appendix 1A).

Table 8.1. Aquatic life use attributes for aquatic life use categories (30 TAC 307).

Aquatic Life Use	Habitat Characteristics	Species Assemblage	Sensitive Species	Diversity	Species Richness	Trophic Structure
Exceptional	Outstanding natural variability	Exceptional or unusual	Abundant	Exception-ally high	Exception-ally 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	Moderately imbalanced
Limited	Uniform	Most regionally expected species absent	Absent	Low	Low	Severely imbalanced

While 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 TIFP. 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 a 5.0 mg/L dissolved oxygen concentration equaled a "high aquatic life use" (6.0=exceptional, 4.0=intermediate, etc.). Consequently, designations in classified segments may not be biologically based in some instances. Second, the Indices of Biotic Integrity (IBIs) now relied upon for assessing aquatic life uses were developed for use in small-to-moderately sized streams and have not been tested extensively in larger rivers such as those selected as priority instream flow segments. IBIs (separately determined for both invertebrates and fish) were also designed to be a multi-stressor indicator of aquatic ecosystem health, and not necessarily designed to be flow sensitive. It is not clear if IBI values 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 is not captured by these designations. The state is committed to protecting designated aquatic life uses and developing recommended flow regimes that will reflect consistency with these designated uses. TCEQ continues to evaluate the effectiveness of all assessment tools including the sensitivity of IBIs to flow variation, and is considering how all stressors, including flow, affect biological integrity. For the purpose of simplicity, it may benefit the TIFP to heed the recommendation of the NRC (2005) and adopt ecological indicators that are linked directly to flow variability (see chapter 4 for more discussion on this topic).

The Texas Surface Water Quality Standards are available on the TCEQ web site at:

http://www.tceq.state.tx.us/nav/eq/eq_swqs.html

8.2.3 Surface Water Quality Monitoring

The Surface Water Quality Monitoring (SWQM) Program has been evaluating biological, chemical, and physical characteristics of Texas' surface waters since 1967. The SWQM program establishes the TCEQ water quality sampling procedures and maintains the TCEQ ambient water quality database collected by the various water quality program partners. This program maintains a large number of fixed sampling sites statewide, performs special studies and intensive surveys to identify causes and sources of pollutants, and quantifies point and nonpoint source loads. It also performs aquatic life use assessments of unclassified streams, receiving water assessments in response to discharge permitting action, and 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 Clean Rivers Program is a collaboration of TCEQ, 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 SWQM program see:

http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wqm/mtr/swqm.html

Details of the Clean Rivers program are available at:

http://www.tceq.state.tx.us/compliance/monitoring/crp/index.html

8.2.4 Texas Water Quality Inventory

The state carries out a regular program of monitoring and assessment to compare conditions in Texas surface waters to established standards and to determine which water bodies are meeting the standards for their identified uses, and which are not. TCEQ works in collaboration with state, federal, regional, and local stakeholders to collect and assess water quality data. The Texas 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 TCEQ web site at:

http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wqm/305_303.html

8.2.5 Texas Pollutant Discharge Elimination System

The state of Texas assumed the authority to administer the National Pollutant Discharge Elimination System (NPDES) program in Texas on Sept. 14, 1998. NPDES is a federal regulatory program to control discharges of pollutants to surface waters of the United States. The Texas Pollutant Discharge Elimination System (TPDES) 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 TPDES program, TCEQ 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 for dissolved oxygen. The type of model used depends on (1) the type of water body, (2) availability of site-specific information, (3) the 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[1] for chronic aquatic life criteria, and one quarter of the 7Q2 for acute aquatic life criteria. A functional aquatic environment with its requisite flows provides assimilative capacity, and TCEQ's water rights permitting program recognizes the important linkage between water quality and quantity by coordinating its recommendations for special conditions for water rights permits with the appropriate water quality programs. While the critical dilution flow is functionally used for modeling parameters such as dissolved oxygen concentrations under low flow, high temperature periods (e.g., worst-case scenario), that does not necessarily imply those flows are suitable for supporting a sound ecological environment on a long-term basis.

For details on TPDES procedures see:

http://www.tceq.state.tx.us/permitting/water_quality/wq_assessment/standards/WQ_standards_implementing.html

[1] The lowest average stream flow for seven consecutive days with a recurrence interval of two years, as statistically determined from historical data (TAC §307.3(a)(48)).

8.2.6 Total Maximum Daily Loads (TMDL)

The Total Maximum Daily Load (TMDL) 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 TMDL 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.

TMDLs must be submitted to the USEPA for review and approval. A TMDL is normally prepared for each pollutant in every impaired water body.
Based on the environmental target in the TMDL, 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 (IP) puts the TMDL into action by outlining the steps necessary to reduce pollutant loads through regulatory and voluntary activities.
The TMDL program is authorized by and created to fulfill the requirements of Section 303(d) of the federal Clean Water Act and its implementing regulations. Detailed information on the TMDL program is available on the TCEQ web site at:

http://www.tceq.state.tx.us/implementation/water/tmdl/index.html

8.3 Water Quality for Instream Flow Studies

The state of Texas has invested considerable resources in the development of water quality models, especially in the TMDL and TPDES programs. The application of water quality modeling approaches used for TMDL development and permitting decisions (TPDES) to instream flow studies will provide consistency among programs; this is particularly important for regulatory programs like TPDES and Water Rights Permitting and for the development and protection of 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 TIFP study design process will be closely coordinated with TCEQ'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, (3) and the constituents of concern. Since TIFP studies 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 (e.g., 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; the volume of flow influences the downstream extent of thermally suitable habitat during all seasons. Several of these species are endemic and are listed as federally endangered. Saunders et al. (2001) evaluated the effects of flow on temperature regimes in the San Marcos River using SNTEMP, a steady-state model that predicts mean and maximum daily water temperature in relation to stream distance (Bartholow 1989).

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 its chemical constituents. Consequently, a longitudinally segmented, one-dimensional water quality model such as QUAL-TX (described by Ward and Benaman, 1999a), a modification of USEPA'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 most commonly applied model 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 dissolved oxygen.

Rivers and streams exhibit seasonally predictable variations in water quality throughout most of Texas. The warmest temperatures (late summer) are typically coincident 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, TCEQ 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 (i.e., high flow pulses and overbank flows) because it is a static or steady-state model. As highlighted in the NRC (2005) review of the TIFP, an ideal model would be capable of simulating water chemistry and temperature under a full range of hydrologic conditions in order to assess the effects of alternative management strategies; be able to 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. Unfortunately, no single model is currently available to accomplish all these feats. Part of the strategy for integration of instream flow study elements will require new ways of thinking about how we model water quality parameters in conjunction with the four flow components. TCEQ 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 are required to 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 TCEQ's existing water quality programs. This will minimize redundancy of efforts and assure consistency among programs.

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9. Integration

The TIFP's purpose is to perform scientific and engineering studies to determine instream flow conditions necessary to support a sound ecological environment in the rivers and streams of Texas. To support that intention, statewide objectives have been developed: conserve biodiversity and maintain biological integrity. In order to meet these objectives and as recommended by the NRC (2005), descriptions of flow conditions will include four components of the hydrologic regime: subsistence flows, base flows, high flow pulses, and overbank flows. These flow components are described further in Table 9.1. 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 inter-annual and intra-annual hydrologic variation.

Table 9.1. 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 Pulse Flows	
Definition:	Short-duration, within 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.

9.1 Subsistence Flows

The primary objective of subsistence flows 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 to ensure a population able to re-colonize the river system once normal, base flow rates return.

Development of recommendations for subsistence flows requires integration of technical studies as shown in Figure 9.1. Biological studies will identify key considerations related to

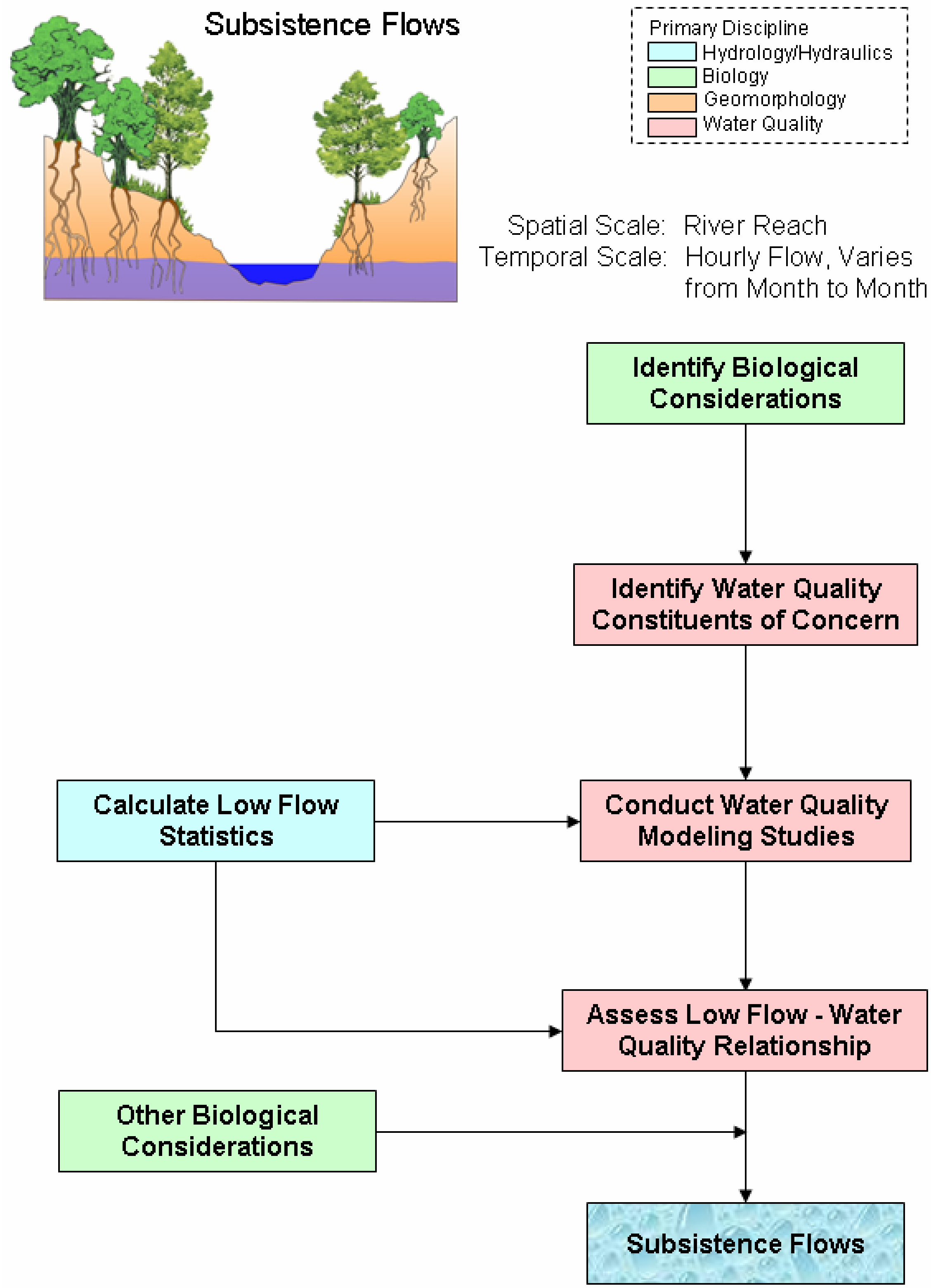

Figure 9.1. Development of subsistence flows from results of multidisciplinary activities.

these reduced flow rates. Examples include identification of location and characteristics of refuge habitat for species during low flow events and descriptions of the effect of such events on important species or communities. Based on these biological and other considerations, water quality constituents of concern will be identified. Examples include stream temperatures and dissolved oxygen concentrations determined to be lethal for certain species or chemical constituents whose elevated concentrations are identified as concerns by stakeholders. Appropriate water quality modeling studies will be conducted to assist in determining the relationship between low flows and constituents of concern (see Chapter 8). 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 flows. Subsistence flow recommendations will be drafted in order to reduce unnatural variation in constituents of concern. After checking their impact on other biological considerations, subsistence flow recommendations will be finalized.

9.2 Base Flows

The primary objective of base flows 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 between years. This variability is essential in order to balance the distinct habitat needs of various species, guilds, and assemblages.

Development of recommendations for base flows requires integration of technical studies as shown in Figure 9.2. Biological studies will identify key species and habitat issues related to the specific sub-basin being studied. Geomorphic studies will assess channel bedform 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, hydraulic modelers will model hydraulic characteristics in relation to flow over the range of interest. A GIS-based physical habitat model will be used to assess habitat versus flow relationships, including diversity (described in Section 9.2.1). Base flow recommendations will include ranges of flow appropriate for wet, normal, and dry conditions as defined by hydrologic studies of the specific river sub-basin. Recommendations will be finalized after assessing biological considerations related to water quality for these flow ranges.

9.2.1 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

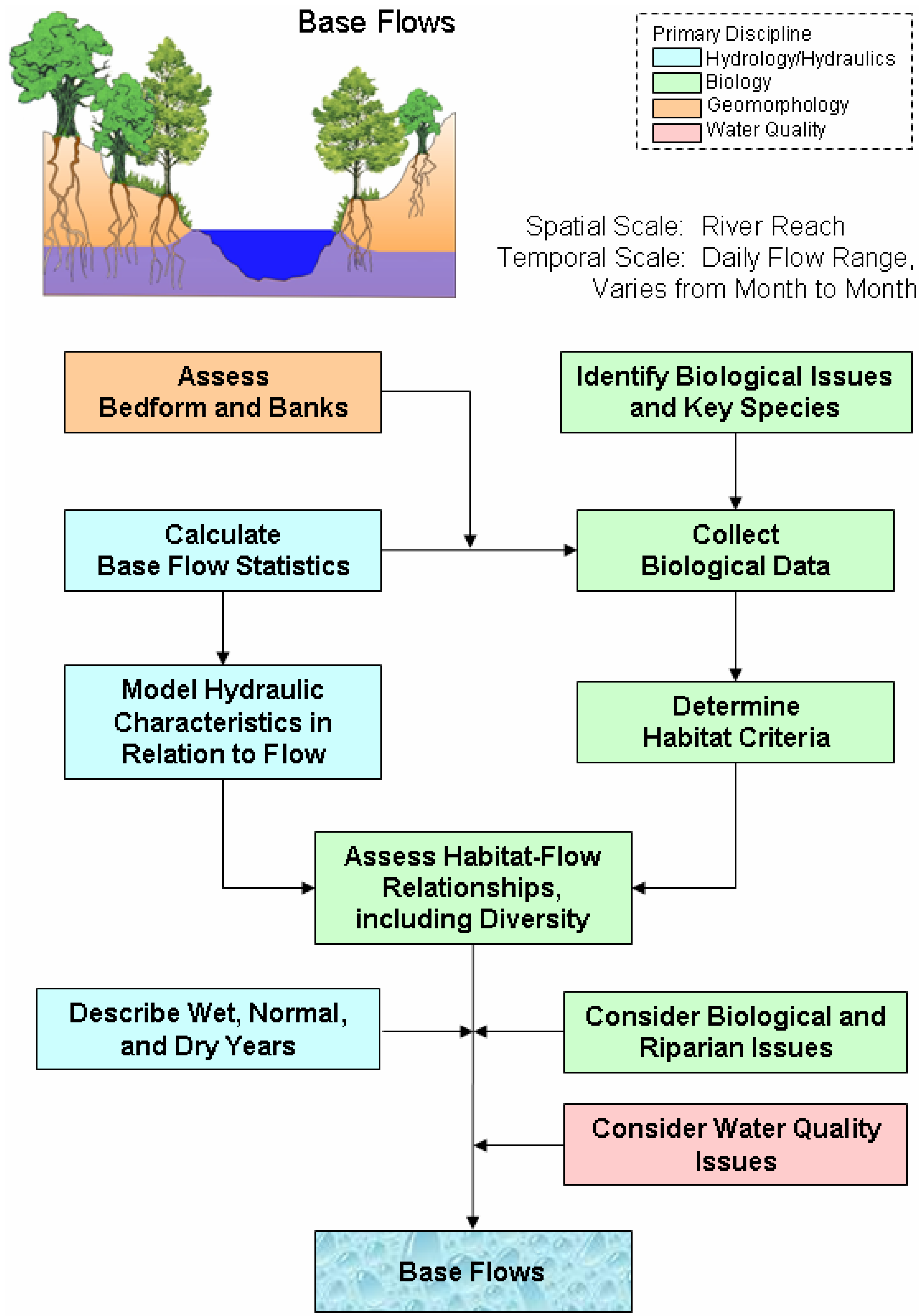

Figure 9.2. Development of base flows from results of multidisciplinary activities.

on how microhabitat suitability changes with respect to stream flow. 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 (e.g., Fragstats) to describe habitat heterogeneity in terms of habitat diversity, patch size, location of edges and transition zones (i.e., 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. Hydrologic time series derived from naturalized and alternative flow regimes will allow comparisons to be made to assess implications of alterations in flow regimes. For example, the percent reduction in habitat area between flow regimes can be calculated to help identify time periods of greater or lesser impact. Indeed, coupled with data on critical time periods of life history events (e.g., 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 (e.g., 85^{th} percentile habitat values; minimum and maximum diversity, etc.) can be calculated. Coupled with habitat thresholds (Capra et al. 1995; Bovee et al. 1998; Saunders et al. 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.

9.3 High Flow Pulses

The primary objectives of high flow pulses will be to maintain important physical habitat features and longitudinal connectivity along the river channel. Many physical features of a river or stream which 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.

Development of recommendations for high flow pulses requires integration of technical studies as shown in Figure 9.3. Geomorphic studies will assess active channel processes that shape the physical features of the riverine system. They 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. In coordination with descriptions of significant habitat conditions determined by biological studies, flow behavior will be used to develop recommendations for high flow pulses. These recommendations will be refined by considering the results of additional studies. Biological studies will identify biological considerations related to high

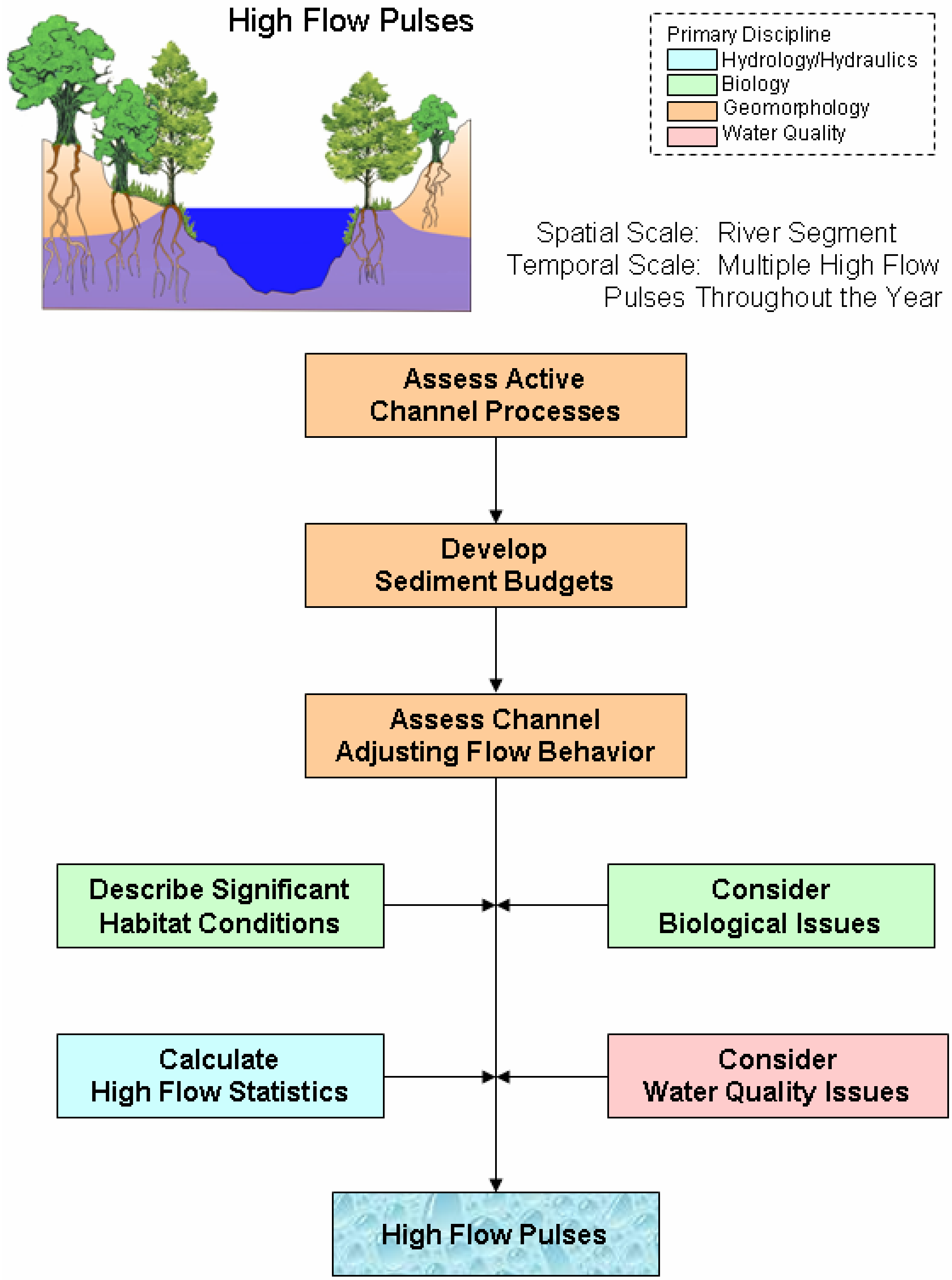

Figure 9.3. Development of high flow pulses from results of multidisciplinary activities.

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.

9.4 Overbank Flows

The primary objectives of overbank flows 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 utilizing floodplain habitat during and after flood events. Secondary objectives for overbank flows may include movement of organic debris to the main channel, providing life-cycle cues for various species, and maintaining the balance of species in aquatic and riparian communities.

Development of recommendations for overbank flows requires integration of technical studies as shown in Figure 9.4. 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 flood events. This information will assist in the assessment of 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 utilizing floodplains. Final recommendations for overbank flows will address all of these considerations.

9.5 Other Considerations

Before final instream flow recommendations are made, the TIFP will consider other factors for a specific river sub-basin that may not have been addressed by technical studies. These factors include compatibility with other state and federal programs related to surface water resources such as freshwater inflow requirements to bays and estuaries and other concerns of a specific river sub-basin. Compatibility with the statutory responsibilities of river authorities and other regional water resource management agencies will be ensured by including these entities as stakeholders during the completion of sub-basin studies.

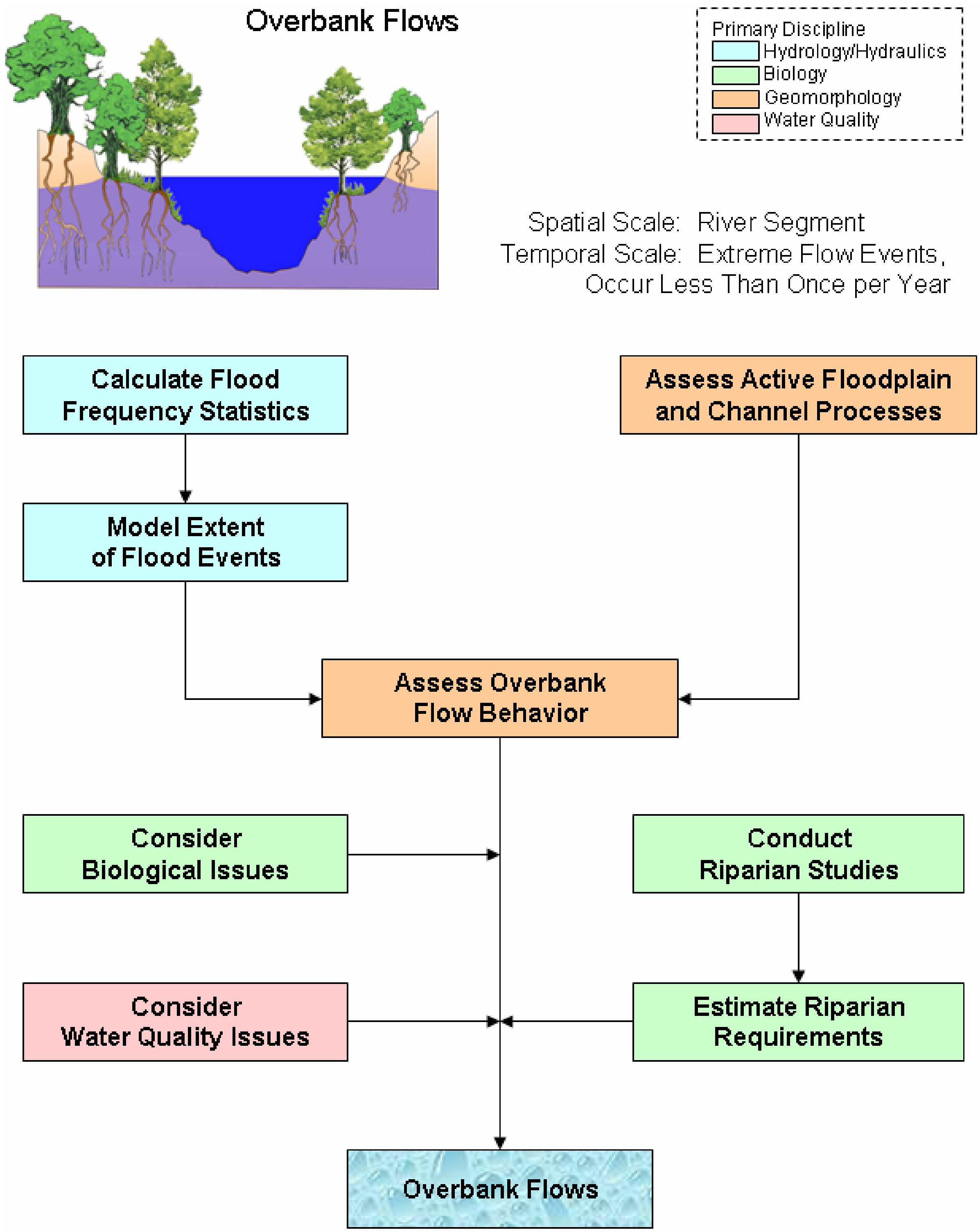

Figure 9.4. Development of overbank flows from results of multidisciplinary activities.

Because the Agencies are directly involved in many of these programs, they are in a unique position to ensure compatibility of the TIFP 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 TWDB and TPWD. The state Total Maximum Daily Load Program required by the federal Clean Drinking Water Act is administered by TCEQ. In the Texas Clean Rivers Program, TCEQ collaborates with 14 partner agencies to conduct water quality monitoring, assessment, and public outreach activities in the state. Statewide water planning efforts mandated by Texas Senate Bill 1 are facilitated by TWDB. Fish and wildlife resources are regulated by TPWD. Through these and other programs and activities, the Agencies have working relationships with many state and federal agencies, allowing communication and cooperation related to program compatibility issues.

9.6 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, base, high flow pulses, and overbank flows. The report will describe the significance of each flow component for the specific river sub-basin. Study methods and analysis techniques will be fully documented.

Each study report will also include descriptions of the scientific realities related to instream flow recommendations for the specific river sub-basin (see section 1.2.2). The study 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 study report will be submitted to scientific peer review, as described in Chapter 3. After completion of any necessary modifications identified by this review, the report will be presented to stakeholders.

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10. Next Steps: Implementation, Monitoring & Adaptive Management

10.1 Introduction

The product of the Texas Instream Flow Program, as envisioned by SB 2, is a series of recommended instream flow conditions that will achieve a sound ecological environment in priority basins. After study reports are delivered to stakeholders, an additional process of implementation will commence to translate those recommendations into action plans. Action plans will outline steps or policies requiring adoption by state agencies, stakeholders, and possibly the Legislature to implement new flow regimes. These plans will also include programs to monitor the aquatic environment to assess the outcome of modified flow regimes, and a framework for adaptive management of flow recommendations. All of these next steps are distinct but follow from many of the technical issues described in this Technical Overview. Success of the Texas Instream Flow Program will, to a large degree, hinge on the topics laid out in this chapter and will reflect the future political landscape, available funding and other resources, and a commitment to the program's goals.

10.2 Implementation Issues

Implementation of SB 2 goals was on the agenda of the 78th Texas Legislative Session when SB 3 was filed. The objectives of this bill included developing a stakeholder process to oversee implementation of SB 2 recommendations. SB 3 was not enacted by the 78th Legislature. However, in partial fulfillment of the bill's objectives, Governor Rick Perry issued Executive Order No. RP-50 on October 28, 2005 establishing an Environmental Flows Advisory Committee. This committee will make "recommendations to establish a process that will achieve a consensus-based, regional approach to integrate environmental flow protection with flows for human needs," and report its findings no later than December 31, 2006.

For each river basin, the full complement of modeling and analysis will be used to derive instream flow recommendations encompassing the complete range of flow patterns that would, collectively, achieve a sound ecological environment. The program is targeting a range of flow regimes, from subsistence to high flow pulses, to ensure maintenance of the variability in physical, biological, and chemical processes through time. Additionally, the range of flow regimes will need to be tailored to specific hydrologic conditions in an implementation plan. For example, annual flow regimes (with monthly or seasonal targets) can be developed for drought, dry, normal, high (wet), and very high (very wet) flow conditions. Specific flow or management objectives would be derived for each of these conditions and implemented on a quarterly basis. For example, during drought conditions objectives might include water quality conditions needed for survival while during very high flow conditions objectives may include, but not limited to, riparian and channel maintenance. Desired habitat conditions or indicators could be developed for each hydrologic condition.

Implementation of flow recommendations will be a pivotal step in the instream flow program. A necessary component of implementation will be striking a balance between human and ecosystem needs 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 ground waters that are hydrologically connected and ever-changing land uses that directly affect watershed dynamics. Different sets of issues will be confronted as the program deals 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 instream flow recommendations are available for a particular sub-basin, water demand may outpace supplies. Innovation will be required to meet instream flow recommendations. Possible mechanisms include encouraging donations to the Texas Water Trust, implementing efficiency measures, modifying dam operations, encouraging land-use practices that maintain or restore healthy terrestrial and riparian ecosystems, and conjunctive use of ground and surface water resources.

An implementation plan will be produced jointly by agency staff and stakeholders (the stakeholder process is described in Chapter 3). Agencies will present study results in a report (see Chapter 9 for additional information) that will form the basis of implementation. Information from that report will be used to revise the conceptual model of the aquatic ecosystem in a specific sub-basin. The report will detail the ecological significance of the range of flows recommended, discuss the uncertainties associated with the analyses, anticipate needs for adaptive management, and describe some of the non-flow related factors affecting ecosystem health. In conjunction with stakeholders, agency staff will review options for adjusting river operations to meet study goals. The implementation plan may also describe topics for additional study should resources become available in the future.

Adaptation of study results by stakeholders to form an implementation plan will require a process facilitated by a neutral party. During that process, the current condition of the aquatic ecosystem will be compared to the desired ecosystem (see Chapter 4) identified through the initial sub-basin stakeholder process (see Chapter 3). A final implementation plan will be formulated after the benefits, costs, and uncertainties associated with specific actions are weighed and constraints are considered. That plan may exceed or fall short of sub-basin goals and the desired ecosystem, but will fall somewhere on the continuum between the state of the current ecosystem and pristine conditions (Figure 10.1).

The TIFP has identified six priority river basins in which to initiate studies and implement recommendations. 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, it is anticipated that classification tools will be developed to aid in the application of instream flow standards to the state's myriad rivers and streams. It would be a near-impossible task to individually study all the state's 191,000 river miles. Derivation of hydrologically, ecologically, and geomorphologically similar aquatic ecosystem units would enable the establishment and application of 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 (Kennan et al. 2006).

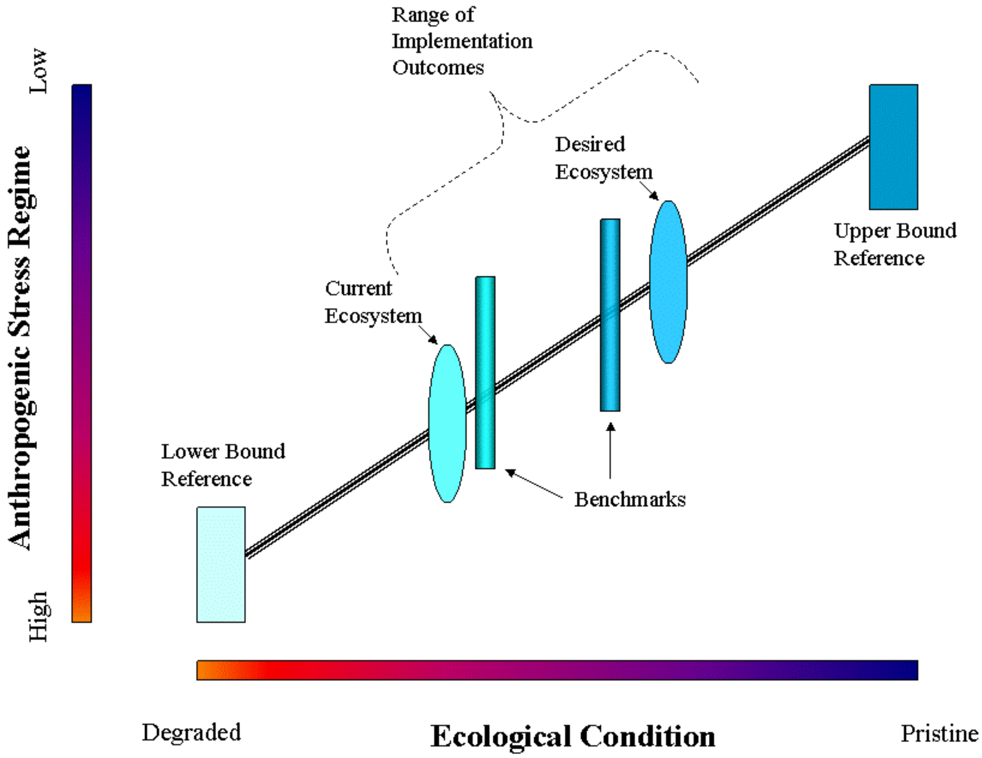

Figure 10.1. The relationship among benchmark, reference, and desired ecological conditions. The upper and lower bounds of conditions for an ecosystem are depicted illustrating the uncertainty associated with defining a specific ecological state. Bars depict benchmark conditions along the continuum that can be used to gauge progress towards a desired state. The various conditions are meant to be representative of natural variability and dynamism. Redrawn from Harwell et al. (1999).

10.2 Monitoring

The effectiveness of implemented flow regimes in meeting resource management objectives should be determined through an effective monitoring program. Monitoring will be considered during the study design phase when goals, objectives and indicators are developed for a sub-basin and initiated after implementation of flow recommendations. 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 where changes in conditions or new information suggest the need, and access to “user-friendly” monitoring information by interested parties.

Networks for monitoring aspects of the state’s rivers and streams already exist (e.g., USGS streamflow gauges, Texas Clean Rivers Program, university studies) and these data sources will be integrated into an instream flow monitoring program. Additional monitoring will 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 will be based on a suite of ecological indicators adapted to:

1. Describe the biological, chemical, physical and hydrologic characteristics of the reach prior to the initiation field studies (establish baseline conditions);
2. Address the goals and objectives of the study recommendations;
3. Be sufficiently flexible to address changing water management strategies;
4. Evaluate the long term effectiveness of permit conditions or operational plans in meeting the stated objectives; and
5. Provide a sound technical basis for recommending adjustments to operational plans in the event that objectives are not being achieved.

10.3 Adaptive Management

The final step of the instream flow program is targeted at addressing the uncertainty of management outcomes that arises 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 et al. 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 achievement of goals. The Texas Instream Flow Program will not be successful if recommendations are implemented but no further analysis of goal attainment is conducted. 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.

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