TEXAS INSTREAM FLOW STUDIES:

TECHNICAL OVERVIEW

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August 8, 2003
DRAFT

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1. Introduction

In 2001, the Texas Legislature enacted Senate Bill 2, which established an Instream Flow Program that is to be jointly administered by the Texas Water Development Board (TWDB), the Texas Parks and Wildlife Department (TPWD), and the Texas Commission on Environmental Quality (TCEQ). The interagency program's purpose is to perform scientific and engineering studies to determine flow conditions necessary to support a sound ecological environment in the river basins of Texas. The goals of the instream flow studies are to conserve biodiversity and maintain biological integrity. The purpose of this document is to outline the technical aspects of instream flow studies as proposed by the interagency science team.

To facilitate instream flow studies, the agencies signed a Memorandum of Agreement in October 2002 that provides a formal process for interagency coordination. A Programmatic Work Plan (Appendix 1A) was approved in December 2002 that identifies priority studies, general methodology, and roles and responsibilities of cooperating agencies. Priority studies are to be completed no later than December 31, 2010.

With the population of Texas expected to nearly double in the next 50 years, from almost 21 million people in year 2000 to about 40 million in 2050, the urgency and seriousness with which the state embarks upon this program is not to be underestimated. At stake are much of the state's irreplaceable natural resources and water supplies for its citizens, its economy, and its environment. According to the 2002 TWDB State Water Plan, if the state does not ensure that there is enough water to meet projected needs, socioeconomic models predict that there will be 7.4 million fewer jobs, 13.8 million fewer people, and 38% less income statewide in year 2050. 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. 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 be exclusively from Texas.

The interagency instream flow program can have a promising and important impact on the future if it successfully provides accurate and useful information for water planning, permitting, and management.

1.1 References

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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, approaches to determine instream flow requirements and predict consequences from flow alteration must be tailored to each individual system.

2.1 Overview of Diversity of Texas Characteristics

A series of maps that illustrate the relevant characteristics of Texas have been included in the map pocket. 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; 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 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 50 inches per year in the east to less than 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. Indeed, 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). Riparian areas vary widely, with those in eastern Texas typically having extensive bottomland hardwoods while prairie streams in northern Texas have vast floodplains. 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 comprised mainly of cyprinids (minnows), percids (darters and perches), catostomids (suckers), centrarchids (sunfishes and basses), ictalurids (catfishes), and nearly 20 other families. Over 50 species of unionid mussels are found in Texas inhabiting rivers, streams, canals, and reservoirs, lakes, and ponds (Howells et al. 1996). Mussel populations in Texas are commercially valuable (shell harvesting) yet little studied. Habitat modification, pollution, commercial harvesting, and the introduction of exotic mussels threaten native freshwater mussels (Howells et al. 1996). Aquatic macroinvertebrates in Texas streams are incredibly diverse, but this fauna remains largely undocumented. It is possible that the number of species of aquatic invertebrates occurring throughout Texas numbers in the thousands. In addition, the biogeographic origins of the faunal elements found in Texas streams are equally diverse with representatives being known from the Gulf Coastal Plain, Chihuahuan Desert, Great Plains, and the Neotropics. Similarly to the fishes, macroinvertebrate diversity and densities are higher in eastern Texas when compared to those of the western portion of the state. Anadromous organisms (e.g., river shrimp or “prawn”) may travel far upstream into rivers, streams, and spring systems to complete their life cycle (Bowles et al. 2000). Texas 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. Instream and riparian habitats have been altered by land-use practices, channelization and other associated 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 in the state with a conservation storage capacity greater than 5,000 acre-feet, only one of which was built before 1900. Some of these reservoirs also provide flood control and contain hydroelectric power facilities. Non-native species introductions have altered the composition of lotic assemblages and in some instances led to the detriment of native species. 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 function and structure of aquatic ecosystems must be preserved. To this end, the scope of studies will address the following riverine components: biology, hydrology and hydraulics, geomorphology, water quality, and connectivity (Annear and others 2002). These 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 includes developing an understanding of relationships between aquatic communities, life histories, habitat (e.g., instream, riparian) and the physical processes that create and maintain habitat, water quality, and the hydrology of the system. Riverine communities include freshwater and estuarine fishes and other vertebrates (e.g., turtles), macroinvertebrates such as caddisflies, stoneflies, mayflies, and dragonflies, mollusks such as mussels and snails, crustaceans such as crayfish and river shrimp, aquatic macrophytes and algae, and riparian flora and fauna. Some species are obligatory 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 good target species for instream flow evaluations.

A central focus of instream flow studies is relating the biology of a system to its flow regime (hydrology) and other riverine components (Bovee et al. 1998; Annear and others 2002). Hydrology plays a key role in determining the composition, distribution, and diversity of aquatic communities. Indeed, riverine biota has evolved life history strategies that correspond to natural flow regimes. Flow regimes largely determine the quality and quantity of physical habitat (see Bunn and Arthington 2002) available to aquatic organisms in rivers and streams. 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; see 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. Connectivity is essential for maintaining important components of stream ecosystems such as survival, growth, and reproduction of many riverine species and the maintenance and function of riparian areas (NRC 2002).

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 (i.e., spawning and recruitment). Information on foraging behavior, habitat use, timing (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. Water quality has a major influence on fish assemblages and varies widely across the state. Conductivity may range from ~100 μmhos in east Texas to more than 100,000 in some west Texas streams. Altering the flow regime may shift water quality and create a system that favors a noncharacteristic assemblage. Elevated water temperatures or low dissolved oxygen concentrations can lead to fish kills or uninhabitable zones. Tolerance levels of fish to low dissolved oxygen, for example, vary among species. 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.) are also important (Stalnaker et al. 1996). With respect to inter-annual variation in flows (between years), short-lived fishes may require certain flow levels every year while populations of long-lived fishes may be sustained by meeting flow needs less frequently. Intra-annual variation in flows (within a year) 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 scales in order to incorporate inter-annual flow variability in an appropriate manner. For example, the life history of a long-lived (decades) species such as paddlefish is different than 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-annual (between years) and intra-annual (within a year or seasonal) 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 for assessing potential impacts to other riverine components. Daily time-steps or shorter are needed to address biological processes such as habitat use and spawning. Flows downstream from hydropower operations 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 both 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 or selection of particular combinations of velocities and depths. A hydrodynamic 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. Such changes directly influence habitat, thus lending support for habitat-based instream flow assessments. Certainly, microhabitat may not be limiting at all flows, but it will be limiting at low flows.

2.2.3 Water Quality

Water quality parameters include temperature, dissolved oxygen concentrations, pH, conductivity, turbidity (fine sediment), and other parameters 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 vary by taxa and life-stage. Factors that influence temperature include streamflow, channel width, thermal inputs, riparian shading, and current velocity. Dissolved oxygen is another important variable that influences survival and distribution of lotic biota since they 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. It is particularly important in studies of alluvial systems. These processes occur over a range of flows and may also differ in terms of duration needed to achieve effects (e.g., days of a certain flow level needed to scour vegetation). Sediment transport processes will vary between basins and are driven by discharge and sediment sizes. Bankfull flows maintain channels, form habitat, and have a recurrence interval ranging from 1.5 to 3 years. Fine sediments accumulate during the receding part of the hydrograph leading to reduced suitability of habitat for spawning, foraging, or refuge (Milhouse 1998). Flushing of fine sediment out of important habitats may occur at flows less than bankfull. Alterations to hydrology influence geomorphic processes by altering the frequency of bankfull events and altering the magnitude, duration, and frequency of flow events that transport or flush sediments.

2.2.5 Connectivity

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 supports 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., floods) and the life history of aquatic and riparian species.

Water development projects and their associated changes in flow regimes influence connectivity. For example, 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 peak 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). At a smaller scale, water diversions can lead to lower water elevations in stream habitats affecting passage of some aquatic organisms.

2.3 Scale and Dimension in Stream Systems

The physical, chemical, and biological processes that facilitate ecosystem function define the boundaries of a stream ecosystem although such boundaries are difficult to define in tangible terms. These processes operate at different spatial scales, which can be expressed in longitudinal, lateral and vertical dimensions, and at different temporal scales often expressed in daily, seasonal, annual, and longer time periods (Ward 1989). Indeed, the spatial and temporal scales of human-induced impact (reservoir operations, diversions, water pollution) and natural disturbance may influence these processes across scales.

The longitudinal dimension of streams refers to processes that operate from headwaters to mouth. The river continuum concept (Vannote et al. 1980) describes general changes in physical gradients and biological attributes facilitated by the unidirectional flow of water and matter. Many studies have been conducted that support, refute, or complement the river continuum predictions. For example, the nutrient spiraling concept (Newbold et al. 1981; Elwood et al. 1983) states that nutrients have open cycles, or spirals because of the dynamics of flow. 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 (Junk et al. 1989) describes the process in which matter (nutrients, sediments, biota) is regularly exchanged between the river and the floodplain. The ecological characteristics and productivity of both the river and the flood plain are linked and influenced by the frequency and duration of flood events. Addressing the vertical and lateral dimensions, the hyporheic corridor concept recognizes the importance of subsurface-surface interactions (Stanford and Ward 1983).

Physical and biological processes also 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 diversion and pumping trends. Stream flows may also vary hourly downstream of hydropower operations. 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.

Particularly important in assessment of instream flow requirements is the scale of stream habitat because processes operating at multiple scales (Poff 1997; Fausch et al. 2002) influence its suitability. Hierarchical frameworks for scaling habitat (e.g., Frissel et al. 1986) facilitate study design and analysis of factors that determine biotic distributions, abundance, and diversity. The relevant scales for lotic species of fish and invertebrates include: basin or watershed, stream reach, channel unit or mesohabitat, and microhabitat (Poff 1997). Key habitat criteria (as well as critical time periods) that operate as filters to influence species distribution and abundance can be defined for each scale. For example, at the microhabitat scale flow dependent species have preferences for faster current velocities perhaps varying for different life history events. At the mesohabitat scale, riffle-dwelling species utilize riffles almost exclusively (at all times) while others may use them only at night. At the reach scale, riparian conditions may influence trophic structure (i.e., the presence of sufficient particulate organic matter input such as leaf matter to facilitate a shredder-dominated community). At the basin or watershed scale, barriers to migration will make some key habitats unavailable at all times. As this framework is broadened to encompass other biological filters, such as temperature and dissolved oxygen requirements, and addressed through time and for each dimension, the need for multi-scale evaluation of instream flow requirements is apparent (Bowen et al. 2003). Indeed, the scale of resource issues must be incorporated into the study design, selection of models and tools, and integration and interpretation of study results.

Evaluations of anthropogenic impacts can be developed for each scale. For example, at the microhabitat and mesohabitat scales, we propose to use hydraulic models to predict changes in habitat. At the reach scale, water quality models, geomorphological evaluations, and specific hydraulic models to address connectivity issues (i.e., riparian zones) will be used in addition to an assessment of ecological health. At the basin scale large-scale anthropogenic impacts will be evaluated and hydrological models will be used to define water “budgets”.

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3. Study Design

During the 1990's, two exhaustive reviews of instream flow assessment programs throughout the United States and Canada were performed. The National Instream Flow Program Assessment (National Instream Flow Program Assessment Steering Committee 2001), and subsequently, Annear et al. (2002) identified a number of specific elements considered essential to the development of effective instream flow programs. These elements were classified as policy components (legal, institutional, and public involvement) or riverine components (hydrology, biology, geomorphology, water quality, and connectivity). The riverine components are technical and can be addressed through appropriate field studies. The policy components represent the socio-economic factors that often limit the state's ability to implement study results. If these constraints are recognized during the early stages of planning, resources can be allocated to study elements that have the greatest value in addressing basin-specific resource management strategies.

3.1 Compile and Evaluate Existing Information

A substantial amount of data has been collected on various aspects of stream ecology for most Texas rivers. These data, however, were collected for a variety of purposes by various public agencies, private consultants, and academic researchers. 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, and physical habitat of the proposed study area. This approach was taken for the Guadalupe River (Longley et al. 1997) and the Trinity River (Kiesling and Flowers 2002). The Trinity River report includes an ArcView Geographic Information System (GIS) tool with spatial coverages and attribute tables for the various data sets.

3.2 Identify Stakeholders and Potential Cooperators

The three state agencies (TCEQ, TPWD, and TWDB) recognize the need to address the concerns of other public agencies and non-governmental groups with a stake in water resource management in each of the study areas. A stakeholder process will be developed to assure that basin-specific issues are adequately addressed during the development of individual study designs.

Groups with stakeholder interest in instream flow issues can be categorized as those with a general statewide interest, such as federal agencies with responsibility for natural resources, and entities with interest in water resource management for specific geographic regions.

Federal agencies with general responsibility for natural resource issues may have an interest in providing input or participating in basin-specific studies. They may also have an interest in collaborating or serving in an advisory capacity on specific study elements such as water quality, hydrology, or biology. Primary federal agencies are:

a. United States Geological Survey (USGS): Has a direct interest in instream flow issues and substantial expertise in the field.
b. United States Fish and Wildlife Service: Primary area of interest is in areas with protected species.
c. Environmental Protection Agency: Has statutory responsibility for environmental protection, including water quality.
d. United States Army Corps of Engineers (USACE): Serves as regulatory authority for wetlands issues (Section 401) and cooperates with local entities on flood control and aquatic restoration projects.

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 1930's, have unique statutory responsibilities as outlined in their respective enabling legislations. The roles of each of these authorities have evolved within the constraints of their statutory obligations, patterns of population growth, and finally the amount of water available. It is anticipated that all appropriate regional authorities will be actively involved as stakeholders for basin specific studies within their jurisdiction and some may have the interest and resources to become active participants in technical aspects of the studies.

Non-profit environmental, recreation, and other interest groups also have interests in instream flows. Environmental groups such as the Sierra Club, National Wildlife Federation, and Environmental Defense Fund should be consulted as stakeholders throughout the process. Additionally, there are organizations such as the Texas River Protection Association and Texas River Recreation Association with interest in specific stream flow issues.

Academic institutions often support programs, either through individual researchers, or through a variety of institutes, with expertise in various aspects of stream ecology, engineering, and water resource management. These resources should be identified and utilized to the extent possible.

3.3 Identify Study Area

Prior to initiating field efforts, it is important to identify the geographic scope of the study. In instances where one or more specific water supply projects have been proposed, the study area may be delineated on the basis of the anticipated zone of impact for that project. Studies that are not project-specific (projected growth and permitting activity, changes in water management strategies such as re-use, interbasin transfers, increased base flow because of municipal discharges, etc.) may include a more generalized area.

3.4 Field Reconnaissance

Once the geographic extent of the study is determined, field efforts should be initiated to select sites for intensive study. The study area is laid out using the following hierarchy:

a. Study Area: The full geographic scope of the study.
b. River Segment: A subdivision of the study area that exhibits relatively homogeneous conditions (biological, hydrologic/hydraulic, water quality) bounded by breaks such as the confluence of major tributaries, significant geomorphic features, etc. The actual number of river segments within the study area depends on the degree of heterogeneity observed. The total length of all river segments is equal to the length of the study area.
c. Representative Reach: A portion of a river segment that represents characteristic elements of the segment; each segment may have one or more representative reaches. The total length of representative reaches within a river segment is usually less than the river segment that it represents.
d. Study Reach: The study reach is a portion of a representative reach that is selected for intensive data collection. Boundaries are usually defined by the habitat or hydraulic model. Each study reach should include a minimum of two sets of characteristic mesohabitats (e.g. riffle-run-pool complexes). One or more study reaches will be selected depending on the distribution of habitat within the representative reach.

Initial field efforts involve air, land, and water level reconnaissance to identify potential representative reaches, study sites, anthropogenic impacts, and existing fish and wildlife resources:

a. 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 good general overview of the study area in a short time frame. Aerial surveys should be performed when flows are at or less than median conditions when habitat features are easier to evaluate.
b. 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.
c. 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, instream cover such as woody debris and boulders throughout the stream segment. Cross-sectional measurements should be 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 conditions when habitat features are easier to evaluate (see 5.2.1).

3.5 Preliminary Biological and Physical Surveys

Initial surveys should be conducted to determine the physical, biological, and water quality characteristics within the study area. TCEQ has standard protocol for determining the appropriate aquatic live use designation for water bodies in Texas. Use Attainability Analyses (UAAs), which include assessments of biological, physical habitat, and water quality, will be performed for each stream segment following U.S. Environmental Protection Agency (USEPA) methodology.

3.6 Develop Geographically Specific Objectives and Study Plans

Tasks to be incorporated into individual study plans will be developed to address technical and policy issues that are identified through the evaluation of existing data, feedback from stakeholders, and field surveys.

3.7 References

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4. Hydrology and Hydraulics

Water diversions affect the frequency, timing, duration, rate of change, and magnitude of streamflow (i.e., flow regime). One component of an instream flow study is an analysis of the effects of potential change in hydrological regimes. The hydrologic and hydraulic evaluation (H & H) element analyzes the existing hydrologic network to develop time series data to quantify alteration in a riverine system, predicts timing of alterations, and also characterizes the physical behavior of water in the system at an ecologically relevant scale. Results of the H & H evaluation are used in analyzing the current conditions and the ecological response to the altered hydrologic and hydraulic conditions.

4.1 Hydrologic Evaluation

Across the state of Texas, natural flow regimes exhibit tremendous variability in instream flows and include extended periods of low flows, flash floods, stable base flows, seasonal periods of low flow, etc. These large variations in the flow regime generally 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 the arid, far west Texas) and in the seasonal patterns of rainfall. Texas has 3,700 named streams and rivers and only very few of these 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 3 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 these seasonal trends and natural flow regimes (Richter et al. 1996). To some degree 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).

In addition to modifying the natural flow regime, impoundments block many aquatic organisms' innate requirement for upstream and downstream migration, act as heat, sediment and nutrient sinks, alter downstream water quality and structural characteristics of stream channels, and fragment aquatic habitats.

Moderation and attenuation of high flows by flood control projects and water supply reservoirs influence the long-standing relationships between streams and the riparian ecosystems associated with that stream. This attenuation disrupts exchanges of nutrients and organic materials, sediments, and water between stream resources and floodplains causing effects on riparian ecosystems. The maintenance of these riparian areas is dependent on the timing, duration, and intensity of streamflows that cause over-banking into primary and secondary terraces, sloughs, adjacent bayous, and other types of riparian wetlands. Lack of over-banking flows shifts the community from hardwood bottomlands toward upland vegetation communities. Bankfull or flushing flows are also important for channel maintenance. If necessary flows (with appropriate magnitude, frequency and duration) are not available for self-maintenance of stream channels, streams tend to accumulate and clump sediments, increase bank erosion rates, and allow vegetative encroachment. These and other processes can result in reduced capacity to efficiently handle flood flows and accumulation of fine sediments.

Additionally, the health and maintenance of various riparian areas, hardwood bottomlands and associated wetland ecosystems is intimately linked to natural flow regimes. 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.

Diminished base flows, largely because of direct diversions, inadequate reservoir releases, and groundwater withdrawals that intercept spring discharge, 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, re-aeration, and thermal buffering capacity and alterations to nutrient dynamics and organic matter processing.

Although low flow events are natural components of flow regimes, humans 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 not be sufficient for survival of many species. Consequently, populations of aquatic organisms needed for recruitment may not exist once streamflows return. The threat of significant 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 at stake when groundwater pumping rates exceed the rate of aquifer recharge. Of the 281 springs identified by Brune (1981) as historically significant, more than one quarter (80) no longer flow, and those that remain have significantly diminished discharges at times.

A detailed hydrologic evaluation is required for a complete and accurate analysis of the effects of a modified flow regime on the river system. The hydrologic evaluation must address runoff inputs, historical flows, naturalized flows, water diversions, water impoundments, flood control structures, and proposed water development projects on the river system. The analysis must consider both intra- and inter-annual flow variations (Richter et al. 1996).

4.1.1 Historical Flows

Historical stream flow information is compiled from USGS and other gauging stations located within the project area. Statistical analysis is performed on the reported daily averaged flows to determine median, average, and percentile flows for each month, season and year. This data can be used to determine wet, dry, and average years (also see 8.8).

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

A gauge site is often not present in the immediate vicinity of the project 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 around the state that flow on an ungaged 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 or prove inaccurate at a particular site, hydrologic models like HEC-HMS (HEC 2001) or TxRR (Matsumoto 1995) that account for land use and soil type may be used to predict runoff from rainfall.

To use a hydrologic model for a rainfall-runoff evaluation, the watershed of the study site must be delineated. Watershed delineation is performed using the best quality topographic information available. Hydrologic Unit Code watershed boundaries are 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 is unavailable, Digital Raster Graphic or USGS 7.5 minute topographic quad sheets are 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/). In practice a lot of this work is more easily handled at least partly in the GIS environment.

4.1.2 Naturalized Flows and Water Availability Modeling

Since natural river flow regimes can no longer be observed on most Texas rivers, 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 the study segment, pre-impoundment flows downstream of the site or flows upstream of the reservoir usually provide a better means to determine naturalized flows at the study site than estimating and accounting for attenuation and losses because of the reservoir.

Water availability models (WAM) used for water rights permitting in Texas utilizes monthly time steps. Monthly summary volumes are, however, inadequate for evaluation of instream flows because they do not account for any hourly or daily variation of flow within a study site. These shorter time scales are just as important to ecological health as the monthly scale and should be analyzed when considering a permit application. Since generation of a reasonable, synthetic, hourly historical dataset is not possible for most projects (except perhaps hydropower projects), the daily time scale is the most easily regulated.

Daily average naturalized flows are calculated by extrapolating monthly WAM naturalized flows output by using daily data from the nearest river gauging station. The volume of daily average flows measured at the gauge station is summed over each month. A flow distribution curve of daily flows normalized to the monthly sum is 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 is measured in a system that may have already been impacted by extractions. The shape of the hydrograph is 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).

4.1.3 Environmental Flows

Some water rights have provisions to allow passage of a finite volume of water through the system to promote a healthy ecosystem in bays, estuaries, rivers, and streams. Most water right permits granted after 1986 in Texas include such provisions. Minimum flows are maintained by placing restrictions on pumping (withdrawals) or placing requirements for pass-through flows on reservoirs. In the absence of a detailed analysis of instream flow requirements for a river segment, a default method is used by the regulatory agency, TCEQ, to determine minimum flow requirements. This method is derived from the Lyons method (Bounds and Lyons 1979). This procedure essentially assigns a fixed percentage to the historical gauged monthly flow at the site.

4.1.4 Flow-Duration Curves

Frequency analysis on the time series of flows can give a good idea of both the "flashiness" of the river and the degree of human impact, when either naturalized flows or pre-development historical flows are plotted for comparison. Flow-duration curves of historical flows are particularly useful for assessing the impact to the hydrological regime of either a new permit application or a modification of an old permit.

Inspection of the flow-duration curve also allows determination of suitable flow rates at which to develop hydraulic models. As a general rule, at least six flow rates are chosen for hydraulic study, from the median flow down to the 10th percentile, plus any other significant flow rates such as those at which biological sampling or other fieldwork took place.

4.2 Hydraulic Evaluation

To analyze fish habitat utilization, water flow patterns of depth and velocity must be resolved to a scale that is sufficiently relevant to fish habitat. However, when comparing the scale of a river segment whose length is measured in tens or hundreds of kilometers to an ecologically important scale (Crowder and Diplas 2000) whose length is relevant to fish habitat measured in meters or decimeters, the determination of sub-meter flow patterns throughout a lengthy river segment is difficult. Consistent with the limitations of available resources, a small reach exhibiting characteristics representative of the larger river segment is studied at the finest scale possible using a numerical hydraulic model.

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

4.2.1 Choosing a Representative Reach

A representative study reach is selected using a combination of biological, water quality, physical, and hydraulic criteria (see 3.4). Within a river segment, one or more reach-length study sites may be selected, each reflecting the unique characteristics of the particular region of the segment. A study reach may be located to address a particular concern in that specific area; for instance, a reach located directly downstream of a proposed diversion may be of particular importance.

The choice of study site length and boundary locations is influenced by many factors, including the requirements for accurate hydraulic modeling. For one-dimensional hydraulic modeling studies and for geomorphologic evaluation, a common rule-of-thumb has historically 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 segment are present. A representative reach whose frequency of pools, riffles, and runs corresponds to the frequency of occurrence of those forms in the segment gives a good representation of the response of the entire segment 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 study reach; extraneous hydraulic model information is removed from the study reach analysis.

4.2.2 Data Collection

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

Flow rate at the study reach is determined by field measurement. A sufficient number of measurements is 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 1.5m, 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 m) and when it is possible to wade across the river hand-held devices are more practical than the ADCP for flow measurement. Additionally, velocity is measured at many places within the study reach and these measurements are used to verify hydraulic model output.

Flow rate measured at the site may be compared with flow rates reported at nearby USGS gauging stations. Flow statistics calculated using historical gauging station data is 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 is performed as described in Hydrologic Evaluation.

Water surface elevation data is collected at upstream and downstream boundaries, as well as at any intermediate areas that exhibit significant changes in water surface slope. Elevation is determined using either traditional differential leveling or vertically accurate GPS techniques. Semi-permanent vertical benchmarks and pressure transducers are installed at the upstream and downstream boundaries and these remain in place for the duration of the study. Downstream water surface elevation measurements are used as a boundary condition for the model. Additional water surface elevation measurements are used for verifying model output.

Bathymetric data is 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 instream 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 the flow patterns within the reach must be resolved at a scale sufficient to model the flow patterns caused by those structures.

Combining flow rate data with water surface elevation data, a rating curve for the study reach is developed and such a curve is used to develop hydraulic models for flow rates where field data is 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 an instream flow study. Alternative linear or polynomial regression analyses may be employed that more accurately describe the observed system behavior at these low flows. 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, then additional site data should be collected to improve the rating at the study reach.

Additional bed and bank elevation data (to further describe the cross-section above the median flow water line), if necessary, may be collected using traditional surveying or other techniques.

See Appendix 4A for a detailed discussion of the data collection methodology.

4.2.3 Hydraulic Modeling

A numerical hydraulic model is used to model the distributions of depth and velocity (i.e., hydraulic habitat) and is used in conjunction with the biological evaluation to evaluate habitat availability under different flow conditions. There are many options for modeling the depth and velocity non-uniformity within a study reach; the most basic option being choice of model dimensionality. One-dimensional hydraulic models (1-D) calculate the average depth and velocity across a section, and multi-dimensional hydraulic models (of both two and three dimensions) are capable of resolving depth and velocity at many points in a cross-section. While a two-dimensional (2-D) depth-averaged hydraulic model has been used most recently for instream flow studies in Texas, other multi-dimensional model formulations may be used in the future according to hydraulic conditions present on a study reach.

One-dimensional hydraulic modeling

Until the mid-1990s, 1-D hydraulic models were used almost exclusively to model channel hydraulics for instream flow studies because they required little computing power and the numerical basis was not difficult to understand. However, since most rivers have spatially complex hydraulic habitat, including across-channel velocity variations, pure 1-D models like HEC-RAS, WSPRO, or SWMM may not resolve channel hydraulics as well as 2-D models (Leclerc et al. 1995; Moyle 1998; Railsback 1999; Crowder and Diplas 2000).

1-D hydraulic models are used for water quality and over-banking flood flow models. Regulatory water quality models traditionally rely upon 1-D hydraulic advection models to determine constituent transport. Modeling of flood flow water surface profiles and over-banking stage can 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.

Multi-dimensional hydraulic modeling

Multi-dimensional hydraulic models offer a number of features that make them favorable for application to habitat studies in rivers. Laterally (across the channel), they quantify circulation patterns, velocity variation, and water surface elevation variation that cannot be quantified with 1-D techniques. Additionally, complicated river structures such as islands, cutoffs, backwaters, and debris can be incorporated into multi-dimensional models (Bates 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 potentially available for use in instream flow studies. The 2-D models historically utilized for river studies are depth-averaged so only horizontal variations in flow are modeled. 3-D models capture both horizontal and vertical velocity variations, which are modeled in vertical layers above each node. 3-D models may be required if strong vertical velocity gradients exist and if knowledge of 3-D flow variation will improve the habitat availability analysis. However, in most cases, a 2-D model will suffice.

There are a myriad of 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.

Governing equations

Multi-dimensional fluid mechanics models applicable to river studies share their root in the Navier-Stokes equations for fluid flow. Since computing 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 far 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 when vertical velocities are evident, and these should not be used where accurate depth and horizontal velocity information is desired. With limitations in mind, a model is chosen that can adequately describe the hydraulic conditions at each 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). The horizontal velocity gradients are more important to overall channel hydraulics than vertical gradients, so a depth-averaged (two-dimensional) model implementing the RANS equations can be used (Leclerc et al. 1995; Vadas and Orth 1998; Lane et al. 1999; Crowder and Diplas 2000).

Instances exist, however, where the shallow water RANS equations may not be strictly applicable, and a model implementing these equations may be occasionally applied outside of the bounds of its stated limitations. Flow velocities in the immediate vicinity (within centimeters) of large woody debris (LWD) may influence the ability of a species to utilize that habitat (Benke et al. 1985), but 3-D flow effects around logs and branches are not resolvable by hydrostatic, shallow water RANS equations (see 4.3). Two-dimensional depth-averaged models have even less applicability when 3-D flow effects dominate.

Vertical velocity variations modeled by a 3-D model may also prove useful for studies of habitat utilization, where different layers of the water column are utilized differently by many aquatic species or where vertical velocity alterations near small-scale impedance structures (debris, boulders, etc.) are important. Until the availability of efficient field data collection techniques to verify 3-D flow effects on habitat utilization improves, the use of 3-D models to evaluate the water column variation in habitat utilization will be limited.

Similarly, modeling of local 3-D velocity variation near structures will be limited because of the extremely small grid scale that is necessary to resolve such variations; however, promising sub-grid scale turbulence modeling has been proposed to address the problem of local velocity variation in the immediate vicinity of LWD (Hodges et al. 2003).

An additional caveat that must be considered is the presence of steep bed gradients oriented in the direction of flow. Steep bed gradients (slopes greater than 20%) of the bathymetry in the direction of flow cause vertical pressure gradients that lead to possible flow separations. Since most 2-D and 3-D models use the shallow-water equations with the hydrostatic assumption, modeling the effect of vertical pressure gradients is not strictly possible with a depth-averaged, hydrostatic model. 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.

Solution methods

Hydraulic models utilizing the finite element (FE) or the finite difference (FD) solution method make up the bulk of the choices of available hydrodynamic models, although finite volume methods are gaining popularity. FE 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 FE models with nodes oriented in geographically correct locations, i.e. with irregular elements that follow the patterns of a sinuous river.

FD 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), an FD model may not perform as well as an FE 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 an FE model. An FD model should, however, be considered for use if some crucial aspect is available in the FD model (for instance, non-hydrostatic solution). FD models are also faster for a given cell resolution than FE models. For models with very fine cells and very large domains, the computational speed of FD models may prove beneficial.

Numerical mesh

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

The mesh boundary is established using a bathymetry data point file that consists of water’s edge horizontal position data. These data are collected at high flows using a laser range finder coupled with a differential GPS. Alternatively, if range finder data are not available, recent Digital Orthographic Quarter Quadrangle aerial photos are used in conjunction with the extents of the bathymetry point file to establish the mesh boundary.

The horizontal distribution of nodes 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 general guidelines 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 an absolute scale that does not resolve the minimum scale resolved by the bathymetry data. Bathymetry significantly affects model output (Carter and Shankar 1997; Lane et al 1999; Crowder and Diplas 2000), so if accurate bathymetry data is 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 is limited by the assumptions of the specific model that is being used.

The horizontal resolution of cells used in the habitat utilization analysis are generally between 2 and 5 square meters, so a hydraulic mesh of comparable resolution will assure adequate resolution of macroscopic velocity fields. Ideally, between 12 and 18 nodes should be spaced across the river width; however, use of a depth-averaged, hydrostatic RANS model reduces the strict significance of apparent modeled velocity oscillations that are shorter than approximately five times the depth. For this reason, cells should not be spaced more closely than approximately five times the depth. The longitudinal to lateral aspect ratio should range from 1:1 to 1:1.5. It can be noted, however, that reasonable model results have been reported when using meshes that are far finer than the model can resolve. While they were far outside the limitations of the model, Crowder and Diplas (2000) went so far as to report exceptional results modeling flow obstructions with RMA-2 using an 8cm by 8cm grid in water of 2-meter depth.

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 typical instream flow study mesh is generated, accurate description of bed form is important for modeling velocity variations. To determine the elevation of the nodes, it is necessary to interpolate from the bathymetry bed elevation data since bathymetry scatter point data resolution may be coarser than the hydraulic mesh. The 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 general 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 prevent use of these techniques since the proportions of anisotropy change with changing flow direction.

To address this problem, the Mesh Elevating and Bathymetry Adjusting Algorithm (Appendix 4B) was developed by TWDB and is utilized for assigning elevation to nodes in the mesh. For applying the anisotropic interpolation, the changing direction of the river flow is taken into account by transforming the Cartesian coordinate system into a coordinate system that follows river planform, defined by distance along flow path and distance from centerline. Rectangular search areas are defined for each node that weight the node (interpolant) 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 (Franke 1982) is utilized to calculate the weighted average of the subset of scatter points.

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 one-dimensional calculations of flow for an entire cross-section (Prasuhn 1987; Arcement and Schneider 1989). The body force calculation is, however, still applicable in 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, 0.1 order of magnitude difference), but the actual value is not more than that, 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 washing machines) that cause local velocity variations are difficult to build into the model. Their physical size is generally 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 effects. For bridge abutments, or large objects that are not submerged at the range of flows and provide complete impedance to flow, 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 the bed forms may change as the energy of the flow changes. River velocity fields have a symbiotic relationship with a mobile bed in that region closest to the bed. The 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 is required.

Objects and bed forms that are clearly mobile at higher flows are a problem. Past experience has suggested 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 is measured. The object may not be there during the next fieldtrip, and another may have appeared, but unless the objects clearly impede the flow on a large scale and affect either or both the upstream and downstream water surface elevations then 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 is discussed in the Physical Processes chapter. Information on substrate can be used to determine a good starting point for the roughness coefficient (Manning’s n) used in the calibration of the hydrodynamic model.

Verification of model output

Verification of model output is performed using data collected in the field (see Appendix 4A). Water surface elevation data, collected at many points throughout the study reach for each flow of interest, are used to verify model water surface elevation output. Point velocity readings, measured during biological sampling, are used to verify model velocity output. Additional point velocity measurements are made for a range of modeled flows in areas where significant hydraulic gradients are present. Horizontal and vertical velocity profiles across an entire cross-section are measured using the ADCP and these measurements are performed at the downstream boundary and in areas where point velocity measurements are not available, not practical, or not sufficient to define the flow.

Verification 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 verification 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 (i.e. RMA-2, FESWMS, CCHE2D, RMA-10, CH3D-WES, EFDC, etc.). 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 availability, array size limitations, or lack of mesh development tools. RMA-2 has been the model selected by TWDB for several recent instream flow studies (Mathews and Tallent 1996; Austin et al. 2003; Osting et al. 2003) for several reasons. 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, 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). Brigham Young University's Surface Water Modeling System (SMS) software for mesh generation and visualization supports RMA-2 (EMSI 2002). Most importantly, RMA-2 resolves flow features to a scale that is relevant to habitat studies.Regardless, as computing power increases or if other models become available that are better suited for specific conditions at a specific site, other models may be used. A brief discussion of the RMA-2 model is included below, but many of the concepts and modeling approaches described are generally applicable to other models.

RMA-2 is a two-dimensional, depth-averaged, finite-element, hydrodynamic numerical model that can solve steady-state and transient problems (for habitat studies, RMA-2 is executed in steady-state mode). 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 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 coefficient, and Eddy viscosity. 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 Pe = fluid density * average elemental velocity * cell length in flow direction / 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 the cell depth, velocity, and length scales, the Peclet number criterion is used to determine the absolute eddy viscosity values. For instream 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 (<5m) as is typical for instream 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 instream flow studies where the same mesh is used at a particular study reach for many models 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 instream flow studies in Texas, some limitations exist that may preclude its use on some study reaches. The model is limited to subcritical flow problems; if instances of supercritical flow exist then another model will be used. The depth-averaged, hydrostatic formulation does not allow for modeling of flow separations in situations of steep local bed slope; if hydraulic conditions on a study reach are dominated by local slope changes, then RMA-2 should only be used with the understanding that the output may have significant errors.

4.3 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 both measure and model. In terms of the hydrodynamics, there are four major issues (Hodges, pers. comm., 2002):

1. The scale of LWD is generally many times smaller than the resolvable flow scales in a typical hydraulic model for a river.

2. The flow effects of LWD are inherently 3-D, while hydraulic models currently used for instream flow studies are either 1-D or 2-D.
3. Flow effects around LWD vary with depth of submergence.
4. LWD is fundamentally ephemeral, so requires either continuous field surveying, acceptance of a "snapshot" in time, or a model, which predicts the collection/removal as a function of river discharge through time.

Whereas there have been considerable advances to the understanding of the ecological function of LWD in Texas (Mathews and Bao 1991; Bao and Mathews 1991; Mathews and Tallent 1996; Mathews and Tallent 1997), there remains much to be determined with respect to the hydraulic function of LWD. Dr. Ben Hodges (University of Texas at Austin, Center for Research in Water Resources) is currently working on a TWDB contract to measure and model the turbulent effects around LWD at the sub-grid scale, and has submitted a proposal to the National Science Foundation (NSF) that addresses the first three issues noted above (Hodges et al. 2003; also included as Appendix 4C).

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5. Biology

5.1 Introduction

Biological evaluations will focus on fish assemblages but may also address other vertebrates, invertebrates, or plants. 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 and interpretation element. Specific information or models may need to be developed to assess riparian areas such as hardwood bottomlands, riparian wetlands, oxbows, and other habitats.

A central focus of instream flow studies is to relate the biology of a lotic system to its flow regime (Bovee et al. 1998; Annear and others 2002). Hydrology plays a substantial role in determining the composition, distribution, and diversity of aquatic communities. Indeed, riverine biota have evolved life history strategies that correspond to natural flow regimes. Many riverine fishes time migration, spawning, and other activities based on seasonal changes in flow regimes (see Stalnaker et al. 1996). Information to address flow needs for key habitats (e.g., shallow mesohabitats) and critical time periods (e.g., spawning and rearing) is an essential element of these instream flow studies.

Flow regimes largely determine the quality and quantity of physical habitat available to aquatic organisms in rivers and streams (see Bunn and Arthington 2002). Channel morphology, the sequence of riffles, pools, and other habitats, and substrate composition result from interactions of flows and watershed geology. Lotic biota respond (in terms of abundance, distribution, and diversity) to changes in physical habitat. Flow dependent species 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 is a primary assumption of habitat-based instream flow models (Annear and others 2002). Habitat complexity (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 (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. 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). 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 support physical, chemical and biological processes in rivers and streams including biogeochemical and nutrient cycling, organic matter and sediment exchange, temperature dynamics (shading), and stabilization of stream banks. Riparian areas often have high biodiversity and biological productivity (NRC 2002). 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).

5.2 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, etc.), environmental requirements (e.g., habitat, temperature, dissolved oxygen), species distributions, community composition, and connectivity considerations.

Existing information will be compiled from agency reports, scientific literature, faunal surveys, and other primary sources. Field surveys will be conducted to determine the distribution of habitats, composition and distribution of aquatic communities, and general patterns of habitat use. These datasets will be used to derive sampling strategies for development of habitat criteria, identify taxa of interest, and assist in delineation of study boundaries and representative reaches. Evaluation of ecological integrity will be assessed at the reach scale.

5.2.1 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 - low slope, smooth, unbroken surface
- Riffle - moderate slope, broken surface
- Rapid - moderate to high slope, very turbulent (e.g. boulder field)
- Chute - very high velocities in confined channel

If the mesohabitat can be further discriminated, it will be assigned a qualifier for relative current speed and depth using fast and slow and shallow and deep. Notes on location and density of woody debris, unique habitat features (e.g., a unique outcrop) and substrate composition will be taken. 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 easier to evaluate.

5.2.2 Fish Surveys

For each study reach, identifiable mesohabitats will be sampled for fish using the most appropriate gear (e.g., seines, electrofishers). Physical measurements will be made in association with each sampling event (e.g., each seine haul). Physical measurements 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 3.3.3); provide data on baseline conditions for monitoring and verification; and allow appropriate biological indices to be calculated. Released fish will be identified, measured, and examined for disease and other anomalies. Voucher specimens will be preserved in 10% formalin for identification quality control checks.

Boat shocking (900 seconds minimum) will focus on habitats too deep or swift for effective backpack or seine sampling (i.e., pools, fast runs, etc.). An attempt will be made to collect all shocked fish (large and small); special effort should be exerted to collect fishes that may be rolling on the bottom. Shocking 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. Shocking time and species enumeration will be recorded for each habitat type sampled.

Backpack shocking (900 seconds minimum) will focus on areas shallow enough for effective sampling (i.e., riffles, shallow runs, etc.). Seines placed downstream of 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. Shocking 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.

5.2.3 Macroinvertebrate 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). The sampling area will encompass an area approximately 1 meter by 0.5 meter directly in front of the collecting net. Three samples each will be collected from riffle, run, and pool habitats 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 95% isopropyl alcohol. The preservative will be replaced with fresh 95% 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 95% isopropyl alcohol. Woody debris will be collected from throughout the study reach and should include well-seasoned 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 should be preserved in 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 should be sorted (in portions as necessary) completely in white enamel or plastic pans with all invertebrates found being stored in individual vials and preserved with 70% isopropyl alcohol. Specimen vials should be labeled to show collection location, type habitat, date collected, and collector. Snag samples should 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 should 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 70% isopropyl alcohol. Snag material should 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
i. Snag samples: number of specimens per cubic centimeter

Meaningful comparison of data metrics is largely dependent on a reference station, when available.

5.2.4 Riparian Area Surveys

Existing information on the location of important riparian features will be compiled from maps, GIS sources, aerial photo and satellite imagery, and other sources. Hardwood bottomlands and other wetland systems (e.g., oxbows) are important riparian habitat types, the evaluation of which may require more detailed information. 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.

5.3 Instream Habitat

Most instream flow studies model habitat availability in response to discharge (Bovee et al. 1998) with the basic assumption being that physical and hydraulic variables determine the spatial distribution of aquatic organisms (Annear and others 2002). 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. Because of resource limitations and time constraints (studies are expected to be completed in 3 to 5 years), data cannot be collected at all flows and high flows present practical difficulties and safety hazards. Thus, representative flow windows are selected for sampling. Habitat modeling provides an extremely useful tool to tell us about conditions that we don't have the time or resources to physically measure. However, modeling involves making extrapolations and assumptions for a full range of conditions and great care should be taken to ensure that they are being applied appropriately; 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.

5.3.1 Quantity and Quality of Instream Microhabitat

One focus of the biology study element is to assess the quantity and quality of instream microhabitat used by lotic organisms and relate that use to stream flow. Several steps are involved in this assessment: (1) sample assemblages and measure habitat conditions; (2) calculate habitat suitability criteria; (3) integrate criteria with simulations of instream habitat over a range of flows; and (4) 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 (e.g., Power 1984) can influence habitat selection and may need to be addressed (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, 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 (fish, other vertebrates, plants, mussels, macroinvertebrates, and macrocrustaceans) 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 cover (Bovee et al. 1998). Other variables may need to be addressed depending on taxa. For example, near-bed hydraulics (e.g., shear stress) have 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, because of the diversity in river characteristics (biology, habitat, etc.) one approach will likely not be suitable for all systems studied; 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); high current velocities may also preclude some sampling locations.

Collection of macroinvertebrate habitat utilization data requires equal-area benthic samplers (e.g., Hess, Surber). 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 affected by reduced flows. Direct visual observations may work well for some taxa 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 studies.

A primary assumption of habitat-based instream flow models is that flow dependent species such as riverine fish tend to show preferences for specific habitat conditions (Annear and others 2002). For example, many darters utilize high velocity, shallow habitat over clean cobble and gravel substrates. Instream cover provides 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 structure 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 5.2.1)
- other hydraulic variables (e.g., shear stress) as required by study design
- location information using position averaging GPS units

An attempt will be made to sample homogeneous patches of habitat, but in some sample units, it may be necessary to average multiple measurements to accurately characterize habitat 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 have high relative elevations. As flows are reduced riffle areas 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 occurs during the spring months when stream flow conditions are higher.

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. Multivariate criteria combine multiple variables (e.g., depth and velocity) simultaneously. 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, species with similar habitat utilization patterns (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 and interpretation 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). 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. However, it may be necessary to generate habitat suitability criteria for individual target species especially those with specialized habitat requirements or specific needs at critical times. Imperiled species may also receive separate attention.

Integrate 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. This study component is discussed further in Integration and Interpretation.

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 H & H) 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).

5.3.2 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). Diverse assemblages are supported by diverse habitat. This relationship is generally accepted (see Ward and Tockner 2001) but other factors (e.g., predation, competition, 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 we believe that this has important implications in the assessment of instream flow needs.

Spatially explicit habitat models, derived from GIS systems and 2-D hydrodynamic models, make available a suite of tools and metrics used in landscape ecology to evaluate spatial heterogeneity of riverine habitat (Bovee 1996; Hardy 1998; Gergel et al. 2002). Software (e.g., Fragstats) enables analysis of spatial patterns and characteristics (e.g., riverine habitat patches) such as patch size, 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 need modification for use 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). This approach is intuitively more biologically sound since it is tied to the use of mesohabitats by lotic organisms. 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 8.2). 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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6. Physical Processes

6.1 Introduction

This chapter includes evaluations of the physical processes that form and maintain the channel, flush and transport sediment, and provide geomorphic mesohabitats and cover (e.g., woody debris, macrophytes, undercut banks).

Streams and rivers transport not only water, but also sediment. Water carries sand, silt, gravel and other material from where it is eroded to where it is deposited in the river channel, floodplain, or the system's delta. The dynamic equilibrium between erosion and deposition creates the river slope and form of the channel forming the physical foundation of instream habitat—riffles, runs, pools, bars and islands, side channels, and other geomorphic mesohabitats.

Rivers adjust to the relative inputs of sediment and flow. The planform, bed slope, flow depth, flow velocity, and shear stress respond to changes in input rates of flow and sediment and the grain size of surface sediment. For example, if there is an increase in sediment load while the flow rate remains constant, then the channel bed aggrades at the point of input, increasing the slope of the river and thereby returning the channel to equilibrium transport condition. Conversely, if the transport capacity is greater than the sediment load, channel widening or scouring may occur.

The downstream effects of dams on rivers are variable and complex (Williams and Wolman 1984; Friedman et al. 1998; Graf 1999; Brandt 2000; Collier et al. 2000; Graf 2001). The sediment-trapping ability of reservoirs can be as high as 99% (Williams and Wolman 1984) and the transport of sediment, especially immediately downstream of dams is limited. Other effects include channel widening and narrowing, scouring or shallowing, and increases and decreases in braiding or meandering. Reservoirs and other water development strategies also alter the hydrology, which in turn influences physical processes and riparian structure and function.

The only fail-safe way to study the effects of a dam is to observe the river channel over time and evaluate changes in its variables. Examples of studies in Texas include the Trinity River's Livingston Dam (ongoing TWDB study) and the Sabine River's Toledo Bend Dam (Phillips 2003).

In an undisturbed lotic system, physical processes should be maintained by a flow regime that addresses valley maintenance, floodplain or riparian maintenance, and channel maintenance including flushing flows to remove fine sediment (Hill et al. 1991). The pattern of these flows varies depending upon the valley and channel type.

6.2 Classifying a River Segment

The most widely used river classification system is probably that developed by Rosgen (1996). The objectives of his hierarchical classification system are "to predict a river's behavior from its appearance, develop specific hydraulic and sediment relationships for a given stream type and its state, provide a mechanism to extrapolate site-specific data to stream reaches having similar characteristics, and provide a consistent frame of reference for communicating stream morphology and condition among a variety of disciplines and interested parties." Rosgen's seven broad stream types are further classified based on measurements of channel cross-section, longitudinal profile, and plan-form features resulting in 41 major stream types.

An important feature of Texas rivers is their inherent "flashiness". The Baker (1977) flash flood magnitude index (FFMI), which is the standard deviation of the logarithms of annual maximum streamflow, varies from about 0.19 for the Calcasieu River in Louisiana to 0.9 for the West Nueces River, near Bracketville, Texas. In addition to classifying the river using Rosgen's procedure, this index should be calculated to provide another way of comparing Texas rivers.

6.3 Assessing the Current Status of the River

A study of the geomorphology of a river should encompass assessment of any recent (perhaps within the past 30 to 50 years) changes that may have occurred to the watershed or channel. These assessments can be based on field mapping, dendrogeomorphology and vegetative evidence, sediment sampling, field observation of flood impacts and analysis of maps, aerial photographs, digital orthophotoquads, and stream gage records. Phillips (2003) describes a good example of how these assessments should be done. Procedures are also described in progress reports for current work on the Trinity River (TWDB subcontract – work in progress).

6.4 Sediment Transport

Sediment transport processes begin with the erosion of soil, rock and organic material in the watershed. That material is then transported by surface runoff to a stream channel. Total sediment load in the channel consists of mineral and organic matter, which is suspended, float load, which is predominantly buoyant organic material, and bedload, which is a much coarser rock material and moves along the channel bottom. Sediment transport through the system will depend on sediment supply and the river's ability to transport that supply.

Sediment loading determines geomorphic features such as sand or gravel bed. The quantity and type of sediment material present affects the stability of the channel, channel slope, and channel features such as mesohabitat.

Sediment movement is required for the ecological health of the river since it is required for creation and maintenance of important physical habitats. For example, riffles in alluvial rivers provide necessary spawning areas for a number of species. They are present where the segment of a meandering stream has straightened out, has a higher gradient than the river in general, and are characterized by shallow, fast flow. If the proper timing and velocity of the flow is not maintained, the riffle will start accumulating fine mineral material and allow algal growth. Accumulation of fine sediments may impair the reproductive success of biota by impeding the movement of oxygen through the substrate.

Particle size distribution also plays an important role. There are different transport relationships depending on the relative amounts of sand and gravel on the bed. If the bed has a very small amount of sand relative to the gravel content, then the sand will move only when the gravel moves, the sand remaining trapped between the gravel. As the sand content of the bed increases, the gravel transport rates increase dramatically although the proportion of gravel in the bed decreases (Wilcock et al., 2001). As the supply of fines increases to a gravel channel, the transport capacity of the channel increases without requiring any change in flow rate.

Large woody debris (LWD) can be thought of as large-scale sediment. LWD is more abundant in smaller streams than larger ones. This is because of the input mechanisms of woody debris, which comes from wind throw, bank cutting, over-bank floods, and fluvial transport in streams. Small streams generally have lower discharges that do not have the ability to move large pieces of wood. Land use and riparian density in the riverine ecosystem affect LWD density in the channel. LWD influences channel form in smaller streams, but has much less influence in large rivers. LWD can change the channel bottom character by creating scour zones. Presence of significant quantities of LWD can cause severe local and channel flow impedance.

6.4.1 Valley Maintenance

Valley maintenance flows are needed to form and maintain valleys. Hill et al. (1991) suggest peak discharges that exceed Q_{25}. However, they caution that establishing or managing for valley-forming flows, if even possible, is problematic due to human developments such as roads and homes. Further, most reservoirs proposed or constructed in Texas do not have the capability to limit flows of the necessary magnitude. Alluvial rivers in Texas may be sufficiently maintained by addressing other physical processes.

6.4.2 Floodplain Maintenance

Riparian or floodplain maintenance events are over-bank floods that are needed to build the floodplain and bring nutrients to the plants that occupy this zone. A practical example in Texas is the dependence of pecan growers on floods to keep trees supplied with sediments and nutrients, where they would otherwise need to use fertilizers.

Whiting (1998) summarized floodplain building into six process classes. These are:
- Lateral point bar accretion;
- Overbank vertical aggradation;
- Braided channel accretion;
- Oblique accretion;
- Counter point accretion; and
- Abandoned channel accretion.

The first two processes are most common, but each can be important depending on the setting.

Whiting (1998) suggests a method where one keeps the flooding flow at or above critical shear stress until the sediment load is greater than the deposition target. This means the approach used will depend on the intended goal. Lateral bar development or bar accretion will require the transport of bed materials, while the vertical accretion of the floodplain surface will require the flow of suspended sediment particles over that area. Frequency, timing and duration of floods are also important to riparian ecosystems; seed dispersal and survival and growth of some species of plants is influenced by the timing and duration of these flows. Recommendations will be made that sustain natural processes.

Determining the magnitude requires very specific knowledge of the flow vs. water surface elevation from historical records, which is unlikely available. In some cases, the FEMA, a local authority or an insurance company, may already have performed flood studies on the river segment. In this case, and if the information is publicly available, surveys and flood maps should be obtained to determine the extent of the floodplain and the frequency at which water moves there. Failing that, on-site surveying and inspection of aerial photographs should be performed and a 1-D model should be developed (perhaps HEC-RAS or Mike-11). 1-D models are discussed in more detail in Chapter 4.

6.4.3 Channel Maintenance

Channel maintenance events are intended to maintain the physical characteristics of the river channel, such as the active channel width, and can be described as the event that transports the quantity and size of sediment without aggrading or degrading the channel.

Determination of channel maintenance flow involves a considerable level of effort, including measurement of suspended sediment and bedload transport at a wide range of flows. This is not practical given the level of resources available. As such, unless a suitable alternative method is identified, the bankfull flow will be assumed to be the minimum channel maintenance flow. Williams (1978) suggests that the bankfull discharge has a recurrence interval of 1.5 years, on average, however the possible range is very wide (Rosgen 1996).

The duration of the channel maintenance flow required is as important as the frequency and magnitude, but not very well understood. Gippel and Stewardson (1995) describe an approach to determine a balance between irrigation needs and the duration, frequency and magnitude of reservoir release for channel maintenance flows for the Thomson River in Australia. Leaf (1998) describes an approach for determining the frequency and volume of water to release for channel maintenance flows for a hypothetical water diversion project. In his example, bypass flows are not required each year, but only when average daily flow reached bankfull or greater.

For the purposes of the state’s instream flow studies, the best approach is probably to examine the historical flows and sediment loading rates (preferably pre-construction or upstream of any reservoirs) and make a recommendation based on the natural shape and duration of the 1.5-year flood hydrograph. This approach would seem sensible as it reduces the likelihood of severe bank erosion because of rapidly dropping flows and it is well known that for the same volume of water, a variable flow is more effective at moving sediment than a steady flow. A suitable alternative, although somewhat more time-consuming, is to physically survey the river reach up into the floodplain and determine the water surface elevation and bank full flow. One would then determine the recurrence interval of that flow rate from a 1-D model and historical flow records and make a flow duration recommendation based on observed hydrographs.

Study of the frequency of occurrence of the naturalized or observed daily, weekly, monthly and annual average flows can give scientists an idea of the impact of current diversions and a sense of what the realistic targets for the river flow ought to be.

6.4.4 Flushing Flows

Flushing flows are important to maintain spawning grounds, food production and channel complexity. When sediment input rates exceed the sediment transport rate then deposition will occur and flushing flows become necessary. Deposition of suspended sediment principally occurs during the receding part of the hydrograph when the river no longer has the energy to hold particles in suspension. The flushing flow can be thought of as the minimum flow required to put these particles back in motion.

The specific objectives of flushing flows are designed for (Kondolf and Wilcock, 1997):

- Restoring/enhancing riffle habitat;
- Removing surficial fine sediment deposits; and
- Removing interstitial fine sediment from gravels.

Ideally, the determination of flushing flow requirements should address three major components (Milhous 1998):

- a biological component that determines the objectives of sediment management in the stream;
- a hydraulic component that determines the conditions needed to accomplish the biological goals; and
- a selection component linking the hydraulic and biological components to determine instream flows needs for the management of sediment.

The first component is discussed in Chapter 5 (Biology). Component 3 is discussed in Integration and Interpretation section (Chapter 8). This section focuses on the second component: the hydraulic conditions needed to accomplish biological goals.

There are a number of ways to determine the need for, timing and magnitude of flushing flows. Annear et al. (2002) have separated these methods into three broad categories: (1) empirical; (2) office based hydrologic methods; and (3) sediment transport modeling.

Empirical field methods involve extensive fieldwork, with measurements of suspended sediment and bedload transport at a range of flows. Movement of painted gravel and change in bed characteristics as determined using core samples or pebble counts, for example, are good indicators of the effectiveness of a particular flow rate at moving sediment. This method requires considerable resources. However, there is a good method that was developed to address the issues of accuracy vs. cost when performing sediment transport studies (see Wilcock and Kenworthy 2002; Wilcock 1997). Research has shown that by separating the sediment into gravel and sand fractions, thoroughness of the study is maintained while the cost and labor is greatly reduced. The most intensive work is the initial sampling, when setting up the transport curve. After that, the model is maintained by visiting the bank. A researcher's eye can be trained to estimate what percent of the bed surface is sand and what percent is gravel. With these updates and knowledge of the flow in the river, a good sediment transport relationship can be developed and maintained for the river.

There are a number of office-based methods to determine flushing flow requirements from analysis of the flow time series. Tennant (1975) suggested that 200% of the mean annual flow produces sufficient depths and velocities to move silt and bedload materials. Office-based approaches offer simplicity at the expense of confidence in the results of the analysis.

There are many sediment transport software packages available, some of which are coupled to the hydraulics, such as GSTARRS 2.1; others such as SED-2d are not coupled to the hydraulics. Being "coupled" to the hydraulics means that as the bed accretes or deforms, so does the bathymetry file used for running the hydraulics (i.e., there is a feedback mechanism). SED-2d has the advantage of accepting RMA-2 output, but it is not coupled to RMA-2, in this sense.

The preferred approach involves combining results of the hydraulic and sedimentological analyses with known relationships between shear stress and sediment transport. Incipient motion analysis can provide a rough idea of the ability of the river to transport sediment. The force provided by the flowing water (bed shear stress) can be computed for a given channel cross-section.

If the actual shear stress exerted by the flow of water exceeds the critical shear stress for the particle size in question then transport may be expected. Depth and velocity output from the hydraulic model can then be combined with information on substrate and mathematically modeled to determine the flow rate at which particles start to move. This information can be used to set a flow requirement for flushing flows. This procedure can be carried out in the GIS environment and is discussed briefly in Chapter 8.

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7. Water Quality

TCEQ’s water quality programs, consistent with the goals and objectives of the Clean Water Act, include measures to assess and protect the physical, chemical, and biological integrity of the state’s water bodies. The scope of this task is limited to the chemical characteristics of water quality; biology and physical processes are separate tasks.

7.1 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 free flowing streams. The native aquatic community of a stream has adapted to a range of flows and the resulting water quality variations over time. However, significant modifications in both flow and water quality have occurred over the last 100 years in direct response to human activities. Rivers have been impounded and diverted, and spring flows have been reduced to provide water for agricultural irrigation, municipal needs, industrial activities, and flood control. Each of these activities have noticeable impacts on water quality, including changes in temperature regimes, sediment transport, and nutrient cycling that are caused by impoundment; increases in temperature, organic loading and nutrients from wastewater discharges, and reduction in assimilative capacity because of reduced volumes of streamflow. 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 can be addressed through effective water 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. 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 October 2002 (TCEQ 2002). Additionally, TCEQ develops a list of impaired stream segments (one or more of the identified beneficial use not supported) as required under section 303(d) of the Clean Water Act.

7.2 Water Quality Programs in Texas

Water quality studies identified as instream flow study tasks will be closely coordinated with TCEQ’s existing water quality programs. This will assure that results and recommendations that are developed are integrated with the state’s water quality standards and regulatory framework. Summaries of applicable programs are presented below; detailed descriptions are located in Appendix 7A.

The Surface Water Quality Monitoring Program has been evaluating biological, chemical, and physical characteristics of Texas' surface waters since 1967. 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 quantify point and nonpoint source loads, 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.

The Clean Rivers Program is a collaboration of TCEQ and 15 water resource agencies (corresponding to the 15 major river basins). 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.

Texas Watch is a volunteer monitoring program that was initiated by TCEQ in 1991 to provide public outreach and involvement in water quality issues. Now administered by Southwest Texas State University under contract with TCEQ, the program has approximately 400 volunteers collecting water quality data from a variety of water bodies statewide.

7.2.1 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 dynamic, flexible cycle of activities to manage water quality. Steps in the cycle include:

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

7.2.2 Surface Water Quality Standards

The Texas Surface Water Quality Standards (TAC 30 §307.7) are rules designed to:

- Establish numerical and narrative goals for water quality throughout the state; and
- Provide a basis on which TCEQ regulatory programs can establish reasonable methods to implement and attain the state's goals for water quality.

All standards are protective; that is, they signal a situation where there is some possibility that water quality may be inadequate to meet its designated uses. For example, there are instances in which a water body fails to meet the standard for aquatic life use but no fish kills have been observed. However, a decline in the diversity and/or number of aquatic organisms, as measured using indices of biotic integrity, could result in a water body being considered impaired.

Segment-specific uses and water quality criteria have been developed for 225 classified water quality segments representing 14,238 miles of perennial streams (Table XX: Atlas of Texas Surface Waters). Aquatic life use designations have been determined for an additional 319 unclassified stream segments totaling over 6,000 stream miles. Water quality standards have been adopted for all streams that have been identified as priority segments in the Programmatic Work Plan (Appendix 1A).

The Texas Surface Water Quality Standards are available on the TCEQ web site at http://www.tnrcc.state.tx.us/permitting/waterperm/wqstand/index.html.

7.2.3 Texas Water Quality Inventory

TCEQ 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 the Texas Clean Rivers Program and other state, federal, regional, and local agencies to collect and assess water quality data. The results of the assessment 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 is an overview of the status of surface waters of the state, including concerns for public health, fitness for use by aquatic species and other wildlife, and specific pollutants and their possible sources. Over 700 water bodies are assessed in Texas; 299 have been identified on the draft 303(d) list for 2002 because they are not supporting one or more beneficial uses.

The Texas Water Quality Water Inventory and 303(d) List are available on the TCEQ web site at http://www.tnrcc.state.tx.us/water/quality/305_303.html

7.2.4 Total Maximum Daily Loads (TMDL)

The state of Texas must develop action plans to remediate those water bodies that are impaired. To restore quality in an impaired water body, it is first necessary to be reasonably certain of the sources and causes of pollution. One way to accomplish this is to develop a scientific model called a total maximum daily load (TMDL). A TMDL:

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

TMDLs must be submitted to USEPA for review and approval. A TMDL is normally prepared for each pollutant in every impaired water body. An external review of modeling approaches for TMDL applications in Texas was conducted by Ward and Benaman (1999a, 1999b), Appendix 7B. They recommended that TCEQ not rely on a specific water quality model or modeling approach when evaluating water quality in Texas.

Detailed information on the TMDL program is available on the TCEQ web site at: http://www.tnrcc.state.tx.us/water/quality/tmdl/index.html.

7.2.5 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 Railroad Commission of Texas.

Under the TPDES program, TCEQ applies 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 needed to protect existing aquatic life uses for classified streams. The type of model to be used depends on (1) the constituents of concern, (2) the type of water body, (3) availability of site-specific information, (4) the location of the discharge point, and (5) availability of previously developed models. A calibrated model is used if available. Permits limits and other special conditions, as appropriate, are determined using established procedures (Appendix 7C).

Since municipal wastewater is the predominant type of wastewater discharge into rivers and streams, much effort has been expended on modeling for dissolved oxygen. It should be noted that fully developed and calibrated water quality models are not available for most classified segments. In the absence of site-specific information, the most commonly applied model is QUAL-TX, a modification of USEPA’s QUAL2E. QUAL-TX was developed specifically for application to Texas rivers and streams. 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.

7.2.6 Water Rights Permitting and Availability

Water in the rivers, streams, underflow, creeks, tides, lakes and every bay and arm of the Texas portion of the Gulf of Mexico is considered state water. Its use may be acquired through appropriation via the permitting process established in Texas Water Code, Chapter 11 and the 30 Texas Administrative Code.

Each application for a permit is reviewed to evaluate its impact on other water rights and existing instream uses. Instream uses are defined as “The beneficial use of instream flows for such purposes including, but not limited to, navigation, recreation, hydropower, fisheries, game preserves, stock raising, park purposes, aesthetics, water quality protection, aquatic and riparian wildlife habitat, freshwater inflows for bays and estuaries, and any other instream use recognized by law.” Special conditions are placed on permits to protect existing instream uses as defined above.

7.3 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.

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 these studies will emphasize rivers and streams, the modeling approaches that have been applied to free-flowing segments are particularly appropriate.

The spatial resolution needed for a model depends largely on the type of water body to be evaluated and it’s hydraulic characteristics. Water quality characteristics 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 advective transport of its chemical constituents. Consequently, a longitudinally segmented, one dimensional water quality model such as QUAL-TX and QUAL-2E are considered sufficient for modeling most stream segments.

Unlike lakes or reservoirs, which tend to exhibit a long-term degradation in water quality because of an inevitable increase in nutrients trapped in the sediments, rivers and streams tend to be replenished during high-flow events that transport sediments and associated nutrients downstream. In recent history, however, nutrients and other contaminants from point sources, primarily municipal and industrial discharges, and from non-point sources resulting from changes in land use in the watershed, have caused noticeable trends in the water quality of almost every river in the state. This has been exacerbated by modifications in flow regimes because of reservoir construction, direct diversions from streams, and increases in base flow resulting from municipal discharges downstream of large population centers. These trends are not constant since the sources tend to change in both the amount and quantity of constituents over time.

Rivers and streams exhibit seasonally predictable variations in water quality throughout most of Texas. The warmest temperatures (late summer) are coincident with the lowest flows of the year, causing stressful water quality conditions. Since this appears to be a fairly 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 described by Ward (1999a).

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).

7.4 References

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8. Integration and Interpretation

The interagency program's purpose is to perform scientific and engineering studies to determine conditions necessary to support a sound ecological environment in the river basins of Texas. To support that intention, specific goals have been developed: conserve biodiversity and maintain biological integrity.

Interpretation involves characterization and quantification of the needs of fish and wildlife resources, determination of consequences of flow alterations, identification of critical resources, and, finally, development of instream flow recommendations. The study will consider the need for a flow regime that incorporates inter-annual and intra-annual hydrologic variation that may be required to meet study goals.

8.1 Framework

A quantitative analysis is performed to identify critical relationships between flow, water quality, physical processes, instream habitat, and the empirically derived habitat requirements of guilds and target species. Other factors such as riparian connectivity, recreation, bay and estuary inflows, and societal and cultural issues are also considered. The framework (Figure 8.1) illustrates the steps needed to develop flow regimes to meet program goals.

8.2 Instream Habitat (Integration and Interpretation of Hydraulics and Biology)

A GIS-based physical habitat model is used to predict habitat conditions within a study reach for a range of simulated flow conditions. Hydraulic models provide the simulated flow conditions; geographic coverages provide information about substrate and cover. This GIS forms a spatially explicit habitat model that can be used to query spatial information. For each simulated flow, the spatial availability of suitable habitat can then be queried using habitat suitability criteria for habitat guilds and target species. For each guild and target species, a microhabitat-discharge relationship is developed to provide information on how microhabitat suitability changes with respect to 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 to describe habitat heterogeneity in terms of habitat diversity, patch size, information on 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 information and 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.

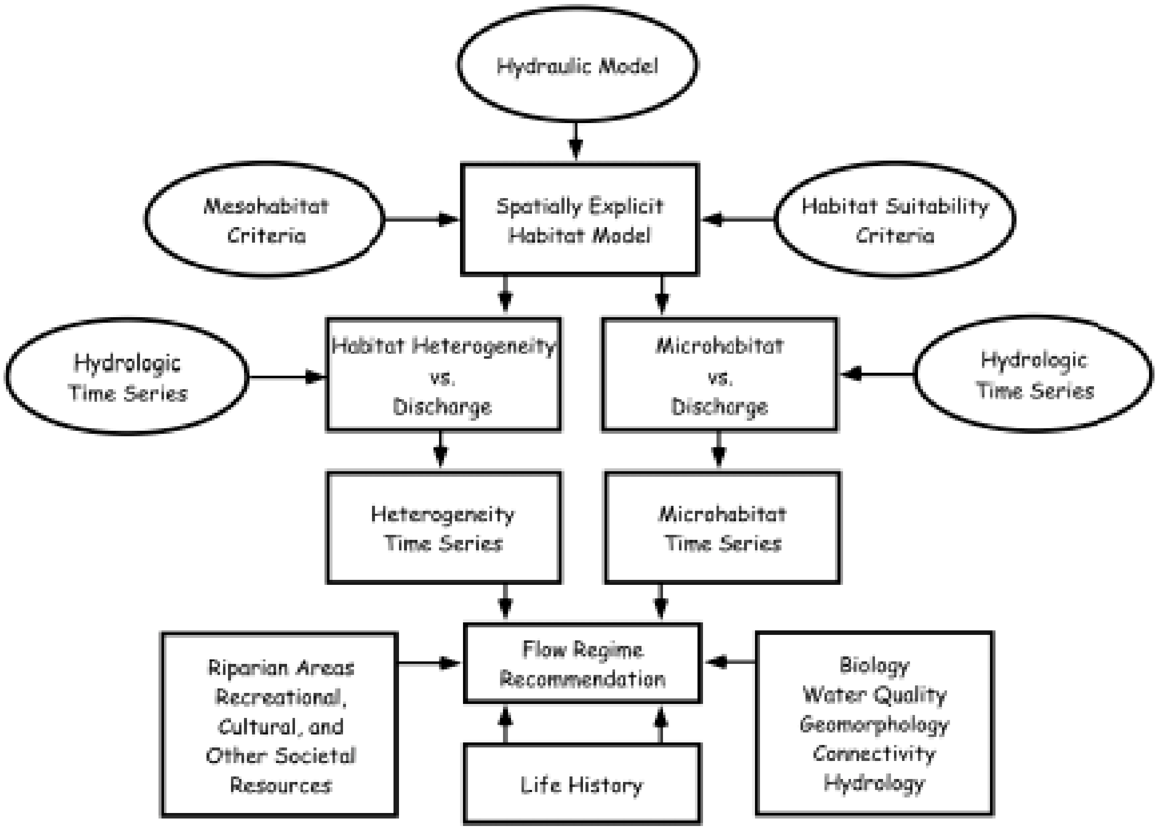

Figure 8.1. Integration of study elements.

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., 85th 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 these spatial and temporal analyses are possible and can be used to identify flow regimes that minimize impacts as defined in terms of microhabitat conditions, key habitats, and habitat heterogeneity. Indeed, maintaining habitat diversity through time and ensuring that key habitats are not lost should be a primary focus.

Results from any special studies to address flow needs of riparian areas will be integrated temporally into habitat-based flow recommendations. For example, high flow regimes for riparian maintenance may only need to be met at intervals greater than one year, which contributes to inter-annual variation in hydrology.

8.3 Hydrology

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). These variables will be addressed by comparing indices, such as the Indicators of Hydrologic Alteration (Richter et al. 1996), derived from naturalized, historical, and alternative flow regimes as well as habitat-based instream flow recommendations.

8.4 Water Quality

Flow regimes identified in the habitat analysis will be assessed in terms of meeting water quality needs (i.e., temperature or dissolved oxygen requirements of biota) and regulatory standards. Adjustments to flow recommendations in some months, seasons, or years may be necessary in order to integrate water quality needs.

8.5 Physical Processes

Flows needed for flushing, channel maintenance, and floodplain maintenance will be integrated temporally into flow recommendations. Flows to maintain these physical processes might be met with some aspects of habitat-based flows and riparian maintenance flows. However, the duration and timing may not coincide and specific flow targets will need to be developed. These targets may vary depending on month, season, or year.

8.6 Other Integration Considerations

Instream flow recommendations will also be assessed in terms of meeting fresh water inflow needs to bays and estuaries, recreation needs, and other societal and cultural flow needs, where appropriate.

8.7 Quantitative Analysis

Quantitative analysis will be performed and will include a combination of statistical, time series, and optimization analyses. Habitat and hydrologic time series analyses have been discussed in previous sections (e.g., 8.2). Statistical analysis varies based on the particular component evaluation but will generally employ standard methods.

8.7.1 Optimization Analysis

Numerical optimization techniques have been used extensively by engineers for calibrating numerical models, optimum sizing of water distribution network pipes, developing operating rules for reservoirs that have to satisfy a number of conditions, etc. (Loucks et al. 1981). Optimization techniques have also been applied to determine bay and estuary freshwater inflow needs in Texas (Longley et al. 1994; Martin et al. 1997; Powell et al. 2002). As long as key factors can be quantified during each component evaluation, optimization routines may be used to identify and evaluate alternative flow conditions that maximize, or at least preserve, ecological health. However, these flow conditions must be evaluated in light of known hydrological and ecological relationships, and professional judgment to ensure that fundamental biological principles and temporal and spatial scales are appropriately considered.

The precise formulation of the instream flow optimization exercise has yet to be defined or tested. Examples that may be explored include minimization of the frequency at which the river experiences flows less than a certain threshold or maximization of the area and duration of particular habitats in a particular season. In practice, the objective function would be set up to consider a large number of constraints, identified in the component evaluations. Satisfaction of certain constraints would be required (e.g., minimum flow to sustain water quality or spawning habitat for an important obligate species) while others may only be desired (e.g., a certain frequency of channel maintenance flow or habitat that benefits a facultative species), thus resulting in weighting of particular constraints based upon importance.

An optimization model will be evaluated using three flow scenarios, as follows: unconstrained, constrained based upon historical flows, and constrained based upon a small change in historical flows. The flow regime resulting from unconstrained model run will likely not resemble any natural or historical flow regime, but will be used to test model response when constraints are added. The constrained historical condition model will be used to test sensitivity of the system when changes of varying degrees are made to the historical flow regime.

For highly complex optimization operations where there are a large number of parameters like those described above, evolutionary algorithms, or, more specifically, genetic algorithms (GA), have been used extensively. Haupt and Haupt (1998) further elaborate on the advantages of GAs over other types of optimization routines. It is expected that GAs will be the optimization methodology chosen for these studies, however given the limited extent to which optimization has been applied to instream flow studies in Texas, it would be prudent to explore other approaches.

8.8 Implementation Issues

For each river basin, the full complement of modeling and analysis will be used to derive instream flow recommendations on a monthly or seasonal basis. It likely will be necessary to consider different instream flow recommendations dependent on the hydrological conditions in the river basin since no single annual flow recommendation will integrate the needs to maintain physical, biological, and chemical processes through time. Water year classes (or other hydrological condition classifications) can be used to dictate which flow recommendation is applicable to those flow conditions. 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 can be derived for each of these conditions. 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 could be developed for each hydrologic condition.

8.9 References

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9. Study Report

This element involves preparation of a study report for peer review and publication. The report should include sections on study area, methods, results, and discussion including a flow recommendation. Focus should be placed on evaluation of fish and wildlife resource impacts because of flow alteration. Although this is one of the last elements in completing a study it is a critical element of study design. For example, decisions about peer review and study authors should be determined during study design.

10. Monitoring and Validation

The effectiveness of implemented flow regimes in meeting the management objectives should be determined through an effective monitoring program. It is anticipated that a monitoring program will be designed to address the specific objectives of each study; however, a common objective of all studies will be to protect existing uses and water quality standards. TCEQ has established surface water quality monitoring procedures that encompass physical, chemical, and biological components. The Surface Water Quality Monitoring Procedures Manual is located in Appendix 4C.

A comprehensive monitoring program should:

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.

Quality assurance and control plans will be developed for each study during study design. Plans for validation of various components of study results will also be developed. Validation of hydraulic and water quality models may require additional empirical data. Habitat model output can be validated through field inspection; for example, re-mapping a study site at a modeled discharge can validate predicted distributions of mesohabitats. Additional biological sampling may be required to validate habitat suitability curves.