Hydraulic Units
Of the Lower Sabine River

Final report—January 2011

Project Report for the Texas Water Development Board and Texas Instream Flow Program, TWDB contract number 1000011022

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Introduction and Background

BACKGROUND AND PURPOSE

This report identifies the hydraulic units of the lower Sabine River, Texas/Louisiana, from Toledo Bend Dam to Sabine Lake, from the perspective of instream flow management. Building on previous work delineating geomorphic zones or reaches (river styles) and geomorphic units, this study addresses the characteristic hydraulic units within those zones. Hydraulic units are ecohydrologic elements shaped by (and influencing) flow-sediment interactions, and providing the physical context for specific aquatic habitats and patch dynamics. The dominant (in terms of size, frequency of occurrence, and influence on hydrologic and ecological conditions) hydraulic units (HU) were identified, described, and related to hydrologic and geomorphic processes. The specific objectives of the project were to:

(1) Identify and describe HUs associated with geomorphic units identified in previous work (Phillips 2008b).

(2) Relate HU inundation to river stages associated with key reference flow levels and recurrence probabilities.

(3) Identify potential changes or disruptions to HUs such as hydraulic removal, desiccation, or burial by sediments.

(4) Develop a conceptual model linking reference flows and effects on geomorphic units and HUs in the lower Sabine.

Hydraulic Units

The study uses the higherarchical framework for river characterization developed by Brierley and Fryirs (2005). The fundamental reach-scale units, river styles or geomorphic zones, are defined on the basis of similarities of channel and valley morphology, channel-floodplain connectivity, dominant hydrologic controls and regimes, and geologic and other constraints. The geomorphic zonation of the lower Sabine is described by Phillips and Slattery (2007) and Phillips (2008a). Geomorphic units (GU) are specific landforms within reaches, e.g. point bars, natural levees, riffle-pool sequences, etc. Geomorphic units are erosional, depositional, or transportational landforms, referred to by Brierley and Fryirs (2005: 26) as “the building blocks of river systems.” Each GU represents a distinct form-process association. GUs are generally capable of significant change on the scale of ~1 year, but may range from ephemeral to persistent due to the episodic, threshold-dependent nature of geomorphic change. GUs of the lower Sabine were identified by Phillips (2008b) and are reviewed in Chapter 2.

Hydraulic units are the most detailed level in the river styles scheme, comprising specific hydrological and ecological elements such as large woody debris, bedforms, aquatic vegetation, and individual flow obstructions or roughness elements. These units are at least potentially capable of significant change over time scales of hours to months, but, again, may range from ephemeral to persistent. Hydraulic units generally comprise the basic habitat elements for aquatic organisms. The technical overview document for the Texas Instream Flow Program (TIFP) calls for instream flow assessments to identify mesohabitats such as pools, riffles, and runs, and to further qualify these based on hydraulics (depth and velocity), substrate, and key habitat elements (TIFP, 2008: 69). A full assessment of the type described in the TIFP is (roughly and approximately) equivalent to a HU. However, the latter are often more specific with respect to hydrogeomorphic elements, more spatially detailed, and include elements not generally encompassed by traditional mesohabitat or biotope identification. This is discussed further in Chapter 3.

STUDY AREA

The study area is shown in figure 1. The Sabine River has a total drainage area of 25,267 km^2, of which 6,676 km^2 (26%) is downstream of the Toledo Bend dam (figure 2). The area has a humid subtropical climate. The river valley in the study area is predominantly forested, except in the lowermost, tidally influenced areas where marshes are dominant.

The lower Sabine is an active alluvial river. It generally has a meandering planform, with active lateral migration and frequent meander cutoffs. Some reaches include active and semiactive anabranches. The geomorphic zonation, as well as the Quaternary geomorphic history, is described in detail in earlier reports (Phillips and Slattery, 2007; Phillips, 2008a).

Hydrology

Study area hydrology is described in more detail in an earlier report (Phillips and Slattery, 2007). This section is condensed from that source.

Runoff and river flow in the lower Sabine River is influenced by the climate and hydrologic response of the drainage basin, releases from Toledo Bend Reservoir, water withdrawals, and tidal and coastal backwater effects (e.g., temporary ponding or upstream flow).

Toledo Bend Reservoir has a controlled storage capacity of 5.522 km^3 (4,477,000 acre-feet). The primary purposes are water supply, hydroelectric power generation, and recreation. The dam is not operated to perform flood control functions. The Sabine River Authority (SRA) of Texas estimates a dependable water yield of 7.07 million cubic meters per day (818 m^3 sec^{-1}). The design flow of the Toledo Bend spillway is 8,212 m^3 sec^{-1} (290,000 cfs). A minimum constant flow of about 5.7 m^3 sec^{-1} (200 cfs) is maintained via the spillway, but most of the flow is passed through the hydroelectric turbines. Maximum recorded release was 3,239.5 m^3 sec^{-1}, and a typical flow during turbine operation is 200 to 300 m^3 sec^{-1}.

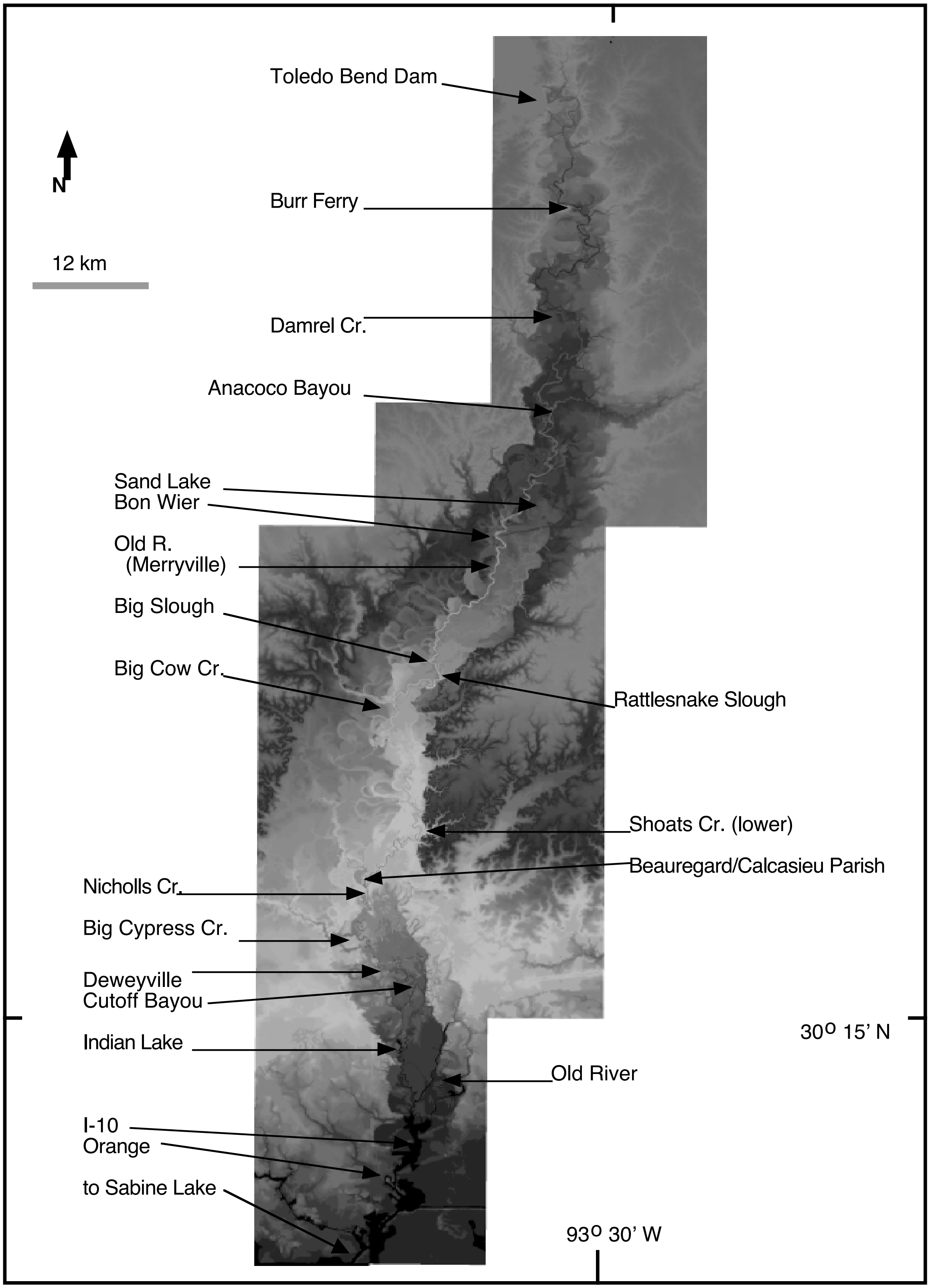

Figure 1. Study area, showing locations of key features and landmarks. Base map is is density plot derived from 30-m DEM data.

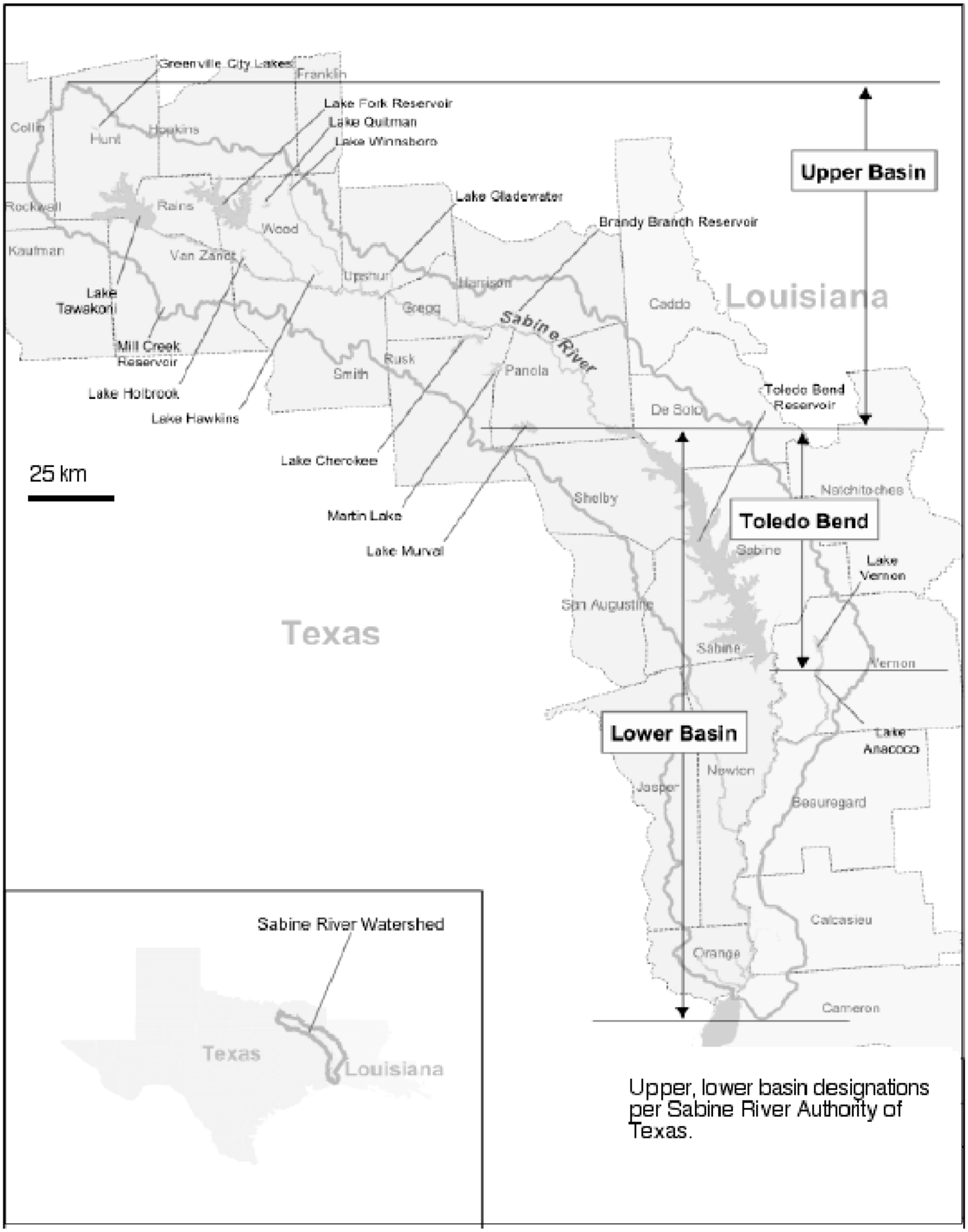

Figure 2. Sabine River drainage basin.

SRA-Texas operates an intake canal on one of the distributary channels of the lower Sabine between Deweyville and Orange. The Gulf Coast Canal system has a capacity of about 600 cfs ($16\ m^3\ sec^{-1}$). This maximum capacity represents about 12.5 percent of median and 6.7 percent of mean flow at the Deweyville gaging station.

Some diversions occur on the Louisiana side, but no data on these are available. Inflow and water balance estimates for the Sabine Lake (Sabine/Neches) estuary, which includes both the Sabine and Neches Rivers and some small coastal basins, are available from the Texas Water Development Board (http://hyper20.twdb.state.tx.us/data/bays_estuaries/hydrologypage.html). Significant diversions between Toledo Bend and Sabine Lake occur only downstream of Cutoff Bayou.

The Sabine River supplies about 46 percent of the freshwater inflow to the Sabine Lake estuary (TCB, 2006). Calculations based on data presented by TCB (2006) show that mean flows at Beckville, upstream of Toledo Bend reservoir, account for about 30 percent of the total outflow of the river. Discharge at Toledo Bend dam represents about 64.5 percent of the flow, with the area between Beckville and the dam contributing about 34.5 percent. The Sabine at Deweyville, about 47 km upstream of the mouth, discharges nearly 95 percent of the total flow, with the basin between Toledo Bend and Deweyville contributing about 30 percent of that. The area downstream of Deweyville contributes about 5 percent of the river outflow estimated by TCB (2006).

Mean and median flows and the one and ten percent probability flows increase as expected downstream within the study reach. The flood stage discharges, however, and thus the recurrence interval of overbank flow, decline (Phillips and Slattery, 2007; Phillips, 2008a). Therefore, overbank flow occurs more often with distance downstream from the dam, and channel-floodplain connectivity is greater. Cross-sectional stream power (the product of discharge, slope, and specific weight of water) for a given discharge at flood stage also generally decreases downstream, and this plus the floodplain inundation reduces sediment transport capacity and increases alluvial deposition. These trends are not unusual for the lower reaches of low-gradient coastal plain rivers (Phillips and Slattery, 2006; 2008; Phillips, 2010).

Previous studies have suggested that releases from Toledo Bend Dam have not significantly changed the discharge regime at Deweyville or inputs into Sabine Lake (Solis et al., 1994; Phillips, 2003; TCB, 2006), and that peak flows and mean flows have been minimally influenced. However, dam releases do clearly influence flows on hourly and daily time scales, and the seasonality of flow. Dam release effects on hydrology diminish downstream from Toledo Bend, and vary inversely with discharge.

Diurnal tidal ranges in the northern Gulf of Mexico are small—generally less than 0.6 m, and in the Sabine are further filtered by the Sabine Lake estuary. Nevertheless, the Sabine River channel is cut to below sea level upstream of Deweyville (where the gage datum is 5.92 feet below sea level (-1.8 m), to at least Big Cypress and perhaps Nicholls Creek.

The tidal signal in the discharge record at Deweyville is barely discernible as a subtle “sawtooth” pattern superimposed on the discharge and stage record.

GEOMORPHOLOGICAL ZONATION AND RIVER STYLES

The geomorphological zonation of the lower Sabine is described in detail elsewhere (Phillips and Slattery, 2007; Phillips, 2008a). The six river styles or zones delineated represent reaches with distinct hydrological characteristics in terms of the relative importance of dam releases and coastal backwater effects, single vs. multi-channel flow patterns, frequency of overbank flow, and channel-floodplain connectivity.

The major zones (reaches or river styles) are shown in Table 1, and their associated hydrologic characteristics and controls in Table 2.

Table 1. Major reaches (river styles) of the lower Sabine River. Locations are in river distance upstream of Sabine Lake in kilometers (Sabine River Authority of Texas river mileages in *italics*).

Reach	*Location*	*Distinguishing Characteristics*	*Primary Geomorphic Controls*
1 Toledo Bend to Burr Ferry	213-192 *146-131*	Incision, steep slope, bedrock control, valley constriction, low sediment loads, pulsed flows	Geologic framework; Toledo Bend Dam releases
2 Burr Ferry to Bon Wier	192-131 *131-91*	Active lateral migration, ubiquitous large point bars, wider valley, larger sediment load	Valley width; avulsion
3 Bon Wier to Big Cow Creek	131-103 *91-70*	Active lateral migration, ubiquitous large point bars, wider valley, larger sediment load; high floodplain/channel connectivity; low slope	Valley width; avulsion; neotectonics
4 Big Cow Cr. to Shoats Creek lower	103-79 *70-54*	Active lateral migration, fewer point bars, high floodplain/channel connectivity, low slope	Neotectonics; valley width; coastal plain paleogeography
5 Shoats Cr. to Cutoff Bayou	79-47 *54-29*	Few and finer-grained point bars, high floodplain/channel connectivity with multiple high flow distributary channels, high sinuousity, embayed tributary mouths	Holocene sea level rise; geology & coastal plain paleogeography; Pleistocene stream capture
6 Cutoff Bayou to Sabine Lake	47-0 *29-0*	Rare point bars; distributary flow network; very high sinuousity; deltaic; tidal influence	Holocene sea level rise; tidal and coastal influences; Pleistocene stream capture

Table 2. Hydrologic regimes in major reaches of the lower Sabine River. Coastal effects refers to influence of tides and coastal backwater effects.

Reach	*Dam pulses*	*Channels*	*Overbank flow*	*Connectivity*	*Coastal Effects*
1 Toledo Bend to Burr Ferry	Flow dominated by dam releases	Single channel	Rare	Low channel-floodplain connectivity	None
2 Burr Ferry to Bon Wier	Flow strongly influenced by dam releases	Single channel	Occasional	Low channel-floodplain connectivity	None
3 Bon Wier to Big Cow Creek	Flow strongly influenced by dam releases	Multiple channels at high flows	Occasional	Moderate channel-floodplain connectivity	None
4 Big Cow Cr. to Shoats Creek lower	Strong influence of dam releases at low flow	Multiple channels at high flows	Occasional	High channel-floodplain connectivity	None
5 Shoats Cr. to Cutoff Bayou	Minor influence	Multiple channels	Common	Extensive connectivity	Minor
6 Cutoff Bayou to Sabine Lake	Minor influence at low flows	Multiple distributary channels	Common	Extensive connectivity	Significant

Chapter 2: Geomorphic Units

INTRODUCTION

Hydraulic units are directly associated with geomorphic units. This chapter is therefore a summary of the geomorphic units identified by Phillips (2008b), which includes more detailed descriptions, and a photographic example of each GU. GUs provide the basis for interpretations of dominant hydrologic and geomorphic processes, and river evolution and behavior. GUs were categorized as mid-channel, bank or bank-attached, and floodplain/valley, acknowledging some fuzziness and overlap in these distinctions.

MID-CHANNEL UNITS

Specific features within channels represent specific process-form associations and/or diagnostics of fluvial processes and evolution. The channel units can be roughly categorized as thalwegs, bedrock outcrops, bars, pool-related units, and large woody debris jams (table 3).

Thalweg. The thalweg is the deepest portion of the channel, defined by connecting the lowest points at any cross-section, and is often thought of as a channel within the channel. All channels contain a thalweg, by definition. At low water when flow is confined to the thalweg, these may correspond to the chute mesohabitats as defined in TIFP (2008).

Bedrock Outcrops. Resistant exposures or outcrops of bedrock locally limit rates of bed and bank incision or erosion, and generally indicate recent erosional removal of Quaternary alluvium. They occur only in the reach from Toledo Bend to Burr Ferry, due to scour following dam construction. These outcrops are particularly common immediately downstream of the dam. The bedrock GUs include mid-channel, channel margin, and cross-channel features.

Bars. Bars in the lower Sabine River are dominantly sandy, though some mud (fine grained) point bars occur in the lowermost reaches, and bars in reaches 1, 2, and 3 may include small amounts of gravel. Bars may be marginal, mid-channel, or connector type.

Point bars occur on the inside of meander bends, and are a common feature of laterally migrating meandering rivers. Point bars are dominantly lateral accretion deposits, associated with erosion of the outside (cutbank) of the bend and deposition on the inside. In general coarser materials tend to be deposited from traction bed load on the upstream end of the bar, and the finest from suspension on the distal end. Thus point bars may have gravel or coarse sand on the upstream end and mud drapes or alternating mud/sand layers are the downstream end. In the lowermost reaches (5, 6) finer-grained point bars occur. Point bars may occasionally be breached by flow along the upper edge of the bar, often by high river flows in combination with surface runoff or tributary inputs.

Table 3. Mid-channel Geomorphic Units of the Lower Sabine River and their association with zones or river styles (see Table 1). Styles in italics indicate that the GU is significantly rarer than in the other listed styles. See Phillips, 2008b, Appendix A for examples.

Geomorphic Unit	Geomorphic Zone (river style)
Thalweg	1,2,3,4,5,6
Bedrock	
Mid-channel	1
Marginal	1
Cross-channel	1
Bars	
Marginal	
Point bar (normal and breached)	
Dominantly sand	1,2,3,4,*5,6*
Dominantly mud (fine-grained)	*5*,6
Lateral bar (normal and breached)	1,2,3,*4*
Tributary mouth (normal and breached)	1,2,3,4,5,6
Diagonal	1,2,3,*4*
Forced	1,2,3,4,*5,6*
Mid-channel	
Forced	1,2,3,*4,5*
Transverse (linguoid)	1,2,3
Compound	1,2,3
Longitudinal	1,2,3
Sand sheet	2
Connector	1,2,3,*4*
Pools	
Riffle-pool sequence	1,2,3,*4*
Circular meander pool	6
Forced pool	
Downstream	1,2,3
Backwater	*1,2,3,4,*5,6
Glide (run)	1,2,3,4,5,6
Large Woody Debris Jams	1,2,3,4,5,6

Lateral bars occur along banks in low-sinuosity reaches. Classic alternate-side lateral bars are rare in the Sabine, but lateral bars do occur in short relatively straight reaches between meanders. These may occasionally be breached, as with the point bars above.

Tributary mouth bars are delta-like features which may occur as deltas *per se* at the tributary mouth, or as spits aligned with the river channel and oriented downstream. These bars may be breached by tributary or river flow, and are associated with backwater effects on the tributary from the river.

Diagonal bars are usually bank-attached in the Sabine, but may also occur as cross-channel features. They are oriented diagonally to banks, with elongate, oval, or rhomboid planform shapes. Diagonal bars are formed where flow is oriented obliquely to the longitudinal axis of the bar, and may indicate reworking of riffles. While diagonal bars are usually associated with gravel or mixed-bed channels, those in the Sabine are predominantly sandy.

Forced bars are associated with sediment trapping behind obstructions, and may occur in mid-channel or attached to banks. All forced bars observed in the study area were associated with large woody debris.

The term transverse bar is used in a general way to refer to cross-channel bars, and in a more specific way in reference to mid-channel bars oriented perpendicular to flow and occupying most of the channel width. These are also called linguoid bars, and are often lobate in shape and have a slip face on the downstream end. They are often found at points of relatively abrupt flow expansion, and in the lower Sabine often occur just downstream (or at the downstream end of) flow constrictions associated with point or lateral bars. Linguoid bars are associated with diverging flow with high availability of sand.

Longitudinal bars are mid-channel features oriented parallel to flow and more-or-less streamlined, often with a downstream-oriented teardrop shape. Longitudinal bars are deposited when transport capacity is exceeded by sediment supply in mid channel.

Changing flow and sediment transport conditions may lead to the formation of several generations of different types of bars in the same location. Further, downstream translation of midchannel bars may result in the welding together of various combinations of point, lateral, diagonal, linguoid, and longitudinal bars. In either case the result may be compound bars, characterized by traits of two or more of the types described above.

Sand sheets are more or less uniform tabular sand sheets occupying the entire channel. They are associated with bedload deposition where sediment supply exceeds transport capacity, and may exhibit a variety of bedforms. At low water, they may resemble braided channels with multiple intertwining subchannels. Sand sheets are readily reworked, and may be translated downstream during floods.

The bar types discussed above are generally recognized in the geomorphology literature (see, e.g., Brierley and Fryirs, 2005). In the lower Sabine an additional class of bar was indentified, termed connector bars. Connector bars extend from the downstream end of a point or lateral bar to the upstream end of a point or lateral bar downstream. They are distinct from the linguoid bars that sometimes occupy the gaps between marginal bars in that they lack obvious downstream slip faces, and are oriented parallel or diagonal to flows.

Pools. Pools are sections of channel with greater depths and lower velocities than adjacent sections. They are often associated with riffle-pool sequences, characterized by shallower, higher-velocity, higher-roughness patches (riffles) alternating with pools. In the study area riffles may be associated with linguoid or connector bars or sand sheets, while pools are often associated with outer portion of meander bends. A glide or run is a plane-bed section of channel that is neither pool nor riffle, associated with an approximate balance between transport capacity and sediment supply.

Forced pools are associated with flow obstructions such as large woody debris. These units may be scour features downstream of resistant bedrock outcrops or large debris pieces, or backwater pools from ponding behind these obstructions. Backwater forced pools are also found immediately downstream of some point bars.

Circular meander pools are, in planform, approximately circular enlargements at the apices of tight meander bends. They are unusually deep, more so than normal meander pools—as much as three times the maximum depth of adjacent sections. At least one circular meander pool occurs in the lower Sabine, and aerial photography suggests other possible occurrences in reach 6.

Large woody debris (LWD; logs, trees, large limbs) is generally considered as hydraulic or microhabitat units rather than a geomorphic unit. However, significant LWD accumulations (jams), as opposed to individual pieces of wood, represent form/process interactions and are thus legitimate GUs. The largest LWD jams occur in tributary mouths, where they may pond or deflect tributary inflow, and reflect backwater flooding and recirculating eddies at high flows, where floating wood is deposited as flows recede. The second largest class of LWD jams occurs along eroding river banks, where rapid recruitment of toppled trees, coupled with entanglement of floating debris, creates the jams. Mid-channel LWD jams are associated with entanglement of LWD with large trees embedded in the bed. These are both smaller and less frequent than the tributary mouth or bank jams.

The geomorphic interpretation of mid-channel GUs is summarized in Tables 4 and 5; see Phillips (2008b) for more details.

Table 4. Geomorphic interpretation of mid-channel geomorphic unit[a] (from Phillips, 2008b). Bars are treated separately in Table 5.

Geomorphic Unit(s)	Contemporary Processes	Geomorphic History	Possible Transformations Or Changes
Thalweg	NA1	NA1	Lateral migration; sinuousity
Bedrock outcrops	Minimal channel incision	Channel incision	Expansion or burial
Riffle-pool	Selective bedload transport	NA1	NA1
Glide (run)	Steady-state sediment transport	NA2	Development of bars, riffle-pool sequences
Circular meander pool	High-flow countercurrents	Slow lateral migration; inhibition of cutoffs	NA2
Downstream forced pool	Scour downstream of obstacle	NA1	Infilling, smoothing
Forced backwater pool	Flow obstruction and ponding	NA1	Infilling, smoothing
LWD jams	Bank erosion, LWD transport, logging waste	NA1	Removal by transport; local bank or bed scour; local backwater effects; avulsion due to flow deflection

[a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information.

Table 5. Geomorphic interpretation of mid-channel bars (from Phillips, 2008b).[a]

Gemorphic Unit (bar type)	*Process Interpretation*	*Geomorphic History/Development*
Forced bar	Deposition due to reduced streampower upstream of an obstacle	NA1
Linguoid (transverse) bar	Flow divergence in conditions of high sand bed load supply; abrupt flow expansion	High sand sediment supply; downstream bar migration
Longitudinal bar	Sediment supply exceeding transport capacity; flow divergence following deposition of coarser sediment the flow is not competent to transport	High sand and/or gravel sediment supply
Compound Bar	Recent variation in flow & sediment transport regime; welding of different bar types due to differential downstream migration	NA1; NA2
Sand Sheet	Local increase in sand supply or decrease in flow competence	Channel aggradation or pulsed bedload transport

[a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information.

BANK UNITS

Bank-attached geomorphic units (Table 6) include the channel banks themselves, and significant subunits along the banks. Geomorphic units that lie partly within the channel (such as marginal bars) are treated in the section on mid-channel units, while GUs connecting the banks and floodplain (such as natural levees and crevasses) are covered under floodplain/valley units.

Benches and Ledges. Benches and ledges are low-relief shelf-like features along channel banks and margins. These features are sometimes termed channel shelves, particularly when no inferences about their origins are drawn. Benches are depositional features related to infilling. They are composed of the same general type of sediments normally comprising the channel bed, bars, and banks, which is typically sand in the Sabine. Ledges are morphologically similar, but are erosional features. Bank erosion may encounter resistant layers which retreat more slowly than less-resistant overlying layers. Ledges of this type are therefore often composed of bedrock or cohesive clays. Ledges may also occur where an episode of incision cuts a narrower channel into the former channel bed. Remnants of the former bed appear as ledges inset into the channel banks.

Ledges of the latter type were not observed on the Sabine, but have been documented on tributaries of the Trinity and Angelina Rivers (Phillips, 2001; Phillips et al., 2005), and may exist on some lower Sabine tributaries, particularly in reaches 1 and 2.

Table 6. Bank-attached Geomorphic Units of the Lower Sabine River and their association with zones or river styles (see Table 2). Styles in italics indicate that the GU is significantly rarer than in the other listed styles. See Appendix A for examples.

Geomorphic Unit	River Style
Bench (depositional)	3,4,5,6
Ledge (erosional)	*1*,2
Bedrock bank	1
Concave bank	1,2,3,4,5,6
Convex bank	1,2,3,4,5,6
Straight bank	1,2,3,4,5,6
Convexo-concave	1,2,3,4,5,6
Concavo-convex	1,2,3,4,5,6
Buttressed (cypress)	3,4,5,6
Slump	1,2,3,4,5,6
Slump scar	1,2,3,4,5,6
Chute channel	4
Sand rampart	2

Compositionally, geomorphic units associated with sandy and muddy material reflect the variety of soils and sediments in the Sabine valley. Banks reflect a large number of combinations of material, morphology, and vegetation cover. The units were identified primarily on the basis of profile (bank top to channel bed) shape, which reflects the cumulative impacts of the interactions among channel and riparian hydrology, bank materials, vegetation, and slope processes (concave, convex, straight, and mixed GUs). Undercut banks, a subcategory of convex banks where a portion of the bank overhangs and shades the water—may be of particular interest for aquatic habitats.

Bald cypress (*Taxodium distichum*) is a common riparian and wetland tree in the lower Sabine, which can grow in saturated or flooded conditions and develops characteristic rampart-like subaerial roots called knees. The wide, buttressed cypress trunks and knees, where they occur along banks, provide a measure of erosion protection. Bald cypress is an obligate wetland plant (grows naturally only in wetlands), but cannot germinate in inundated conditions. Thus cypress growing in conditions of normally standing water indicates a local rise in water level subsequent to tree establishment, or distinct seasonal variations in water level.

Rotational slumps may occur along eroding concave banks, where significant vertical variations in material properties due to soil strength and/or root mats results in rotational failures. Active slumps are typically characterized by one or more trees and associated understory vegetation with a root mat holding the slumped material together. Eventual removal or dispersal of the slumped material leaves a characteristic scallop-shaped slump scar.

Other Bank-Attached Units. Bedrock banks occur in reach 1, associated with the bedrock channel units, and are likewise associated with post-dam channel scour. Chute channels are high-water channels across point bars, which may eventually lead to chute cutoffs. Sand ramps are sandy bank deposits observed in reach 2 that extend from channel to the natural levee. These are distinct from marginal bars in that the latter do not extend to the top of the banks, and from point bars in that the sand ramps are much narrower and do not occur on the inside of meander bends. Little is known of these features, but their position in the channel and the presence of organic layers within the sand suggest that they result from flow obstructions and temporary backwater effects during high flows. The geomorphic interpretation of bank-attached GUs is summarized in Tables 7 and 8; see Phillips (2008b) for photographic examples and more details.

Table 7. Geomorphic interpretation of bank-attached geomorphic units[a] (from Phillips, 2008b). Bars are treated separately in Table 8.

Geomorphic Unit(s)	*Contemporary Processes*	*Geomorphic History*	*Possible TransformationsOr Changes*
Bench	Infilling	NA1	NA1
Ledge	Bank or bed erosion	Incision into former channel bed	NA1
Bedrock bank	Minimal bank erosion	Channel widening and/or downcutting	NA1
Concave bank	Erosion and bank retreat	Lateral channel migration or widening	Stabilization and recovery to concavo-convex
Convex bank (vegetated)	Bank stability or slow accretion	NA1	Conversion to concave, straight, or complex erosional forms
Convex bank (unvegetated)	Recent or chronic accretion; marginal bar development	NA1	Stabilization to vegetated convex bank
Straight bank (vegetated)	Stable or slowly eroding banks in cohesive materials	NA1	Conversion to concave, straight, or complex erosional forms; conversion to stable convex form
Straight bank (unvegetated)	Bank erosion, lateral channel migration	NA1	Conversion to concave, or complex erosional forms; stabilization to vegetated straight bank
Convexo-concave bank	Erosion of banks of variable resistance; removal of lower bank vegetation or LWD; local low-flow acceleration or deflection	Transition from stable or accreting to eroding bank	Conversion to concave erosional bank
Concavo-convex bank	Recent cessation or deceleration of bank erosion	Recovering cutbank	Conversion to stable convex or concave erosional bank
Cypress buttress	Recent channel aggradation; or seasonal water level variation	Channel aggradation	Erosion, drowning of cypress

Continued from previous page			
Slumps & slump scars	Rotational bank slope failures	Channel incision and/or lower bank erosion	Conversion to or incorporation into concave erosional bank
Chute channel	Concentrated high flow across point bar	Meander development and migration	Chute cutoff or point bar breaching
Sand rampart	Localized marginal deposition	NA2	Removal

[a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information.

Table 8. Geomorphic interpretation of marginal bars (from Phillips, 2008b).[a]

Gemorphic Unit (bar type)	*Process Interpretation*	*Geomorphic History/Development*
Point Bar (active)	Meander growth & migration; deposition at bend apex coupled with cutbank erosion	Meandering, lateral channel migration
Point Bar (stabilized)	Sedimentation dominated by vertical accretion; limited lateral migration; vegetation establishment	Meander stabilization
Lateral Bar	Lateral accretion associated with meandering of thalweg within banks	Possible precursor to meander formation & growth
Breached Point or Lateral Bar	Erosional dissection of bar during rising stage of high flow	Possible precursor to chute cutoff
Tributary Mouth	Deposition associated with reduced stream power at junction; short-term changes reflect relative dominance of river and tributary flows	Lags in watershed sediment transport; adjustment of junction angles
Diagonal	Oblique flow relative to bank	May be associated with high sediment loads relative to transport capacity, or reworking of riffles
Forced	Deposition due to reduced stream power upstream of an bank-attached obstacle	NA1

[a] [a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information.

FLOODPLAIN/VALLEY UNITS

Floodplain and river valley geomorphic units are listed in Table 9. Some are inundated only during extreme valley-filling floods, and are of limited relevance to HUs for instream flows. The latter will not be discussed below.

Table 9. Floodplain and alluvial valley Geomorphic Units of the Lower Sabine River and their association with zones or river styles (see Table 2).

Geomorphic Unit	River Style
Abandoned channel (infilled)	2,3,4,5,6
Abandoned channel (semi-active, high flow)	2,3,4,5,6
Anabranch	5,6
Delta distributary	5,6
Alluvial distributary	3,4
Billabong (slough)	2,3,4,5,6
Low-flow tributary/high-flow distributary or anabranch	3,4
Tie (batture) channel	2,3
Alluvial/colluvial fans or wedges (valley wall)	1,2,3,4,5,6
Backswamp, ridge-and-swale	1,2,3,4,5
Backswamp, flat	4,5,6
Pleistocene meander scars/depressions	1,2,3,4,5
Cutoff meander	3,4,5
Oxbow lakes or swamp	1,2,3,4,5,6
Infilled oxbow	1,2,3,4,5,6
Crevasse splay	1,2,3,4,5,6
Crevasse channel	2,3,4
Natural levee	1,2,3,4,5,6
Island	5,6
Tributary	1,2,3,4,5,6
Alluvial terrace	1,2,3,4,5,6

Abandoned Channels. Channel shifts significantly longer than a single meander loop are called avulsions, and result in anabranches or in abandoned or paleochannels. Avulsions occur throughout the study area on the historic and Holocene time scale, with the exception of reach 1. The distinction among other abandoned channels depends on their age, rate of infilling, and frequency of flow. Infilled abandoned channels have accreted to nearly the level of the surrounding floodplain surface, and do not convey flow, except perhaps as part of general down-valley flow during large floods. Semi-active channels convey flow during high flow events (but not necessarily overbank), but are dry during low and normal flows. Billabongs are channel remnants which are not fully infilled and usually hold ponded water, but have no hydraulic connection to the main channel except during floods. The term billabong rather than slough is used because the latter term is used to refer to a variety of different features.

Cutoffs and Oxbows. Cutoff meanders as listed in Table 9 refers to recently cut off features which are still within a few channel widths of the (new) active channel. Older cutoffs (oxbows) occur in various states of infilling—oxbow lakes, swamps, and infilled oxbows. In some cases tie channels (or batture channels) connect oxbows or billabongs to the river. These channels may alternately drain or fill the floodplain features, depending on hydraulic conditions.

Levees and Crevasses. Natural levees are ridges just above the bank tops, at the outer edge of the floodplain. Breaches of the levee from the river side are crevasses. Where flows diverge on the floodplain side of the levee, flow decelerates rapidly and sediment is deposited in fan-like deposits called crevasse splays. Rapid vegetation establishment and litter coverage in southeast Texas make splays difficult to observe in the field in forested settings unless they were recently deposited. When crevasses lead to concentrated flow and channels are incised, crevasse channels result.

Floodplain Depressions. Alluvial floodplain evolution may result in depressional areas in the valley bottom other than oxbows, billabongs, and abandoned channels. Backswamp is a general term for lower areas behind the natural levee, but more specific backswamp features are associated with ridge-and-swale topography. Geomorphic zones 1-3 are dominated by ridge-and-swale topography, and reach 6 by generally lower-elevation flat backswamps with few ridges. Reaches 4-5 are transitional, and include both general types of backswamp. Rivers of the southeast Texas coastal plain experienced higher mean discharges during the Pleistocene, with larger channels and meanders with substantially larger amplitudes and wavelengths than the contemporary rivers. In the Trinity-Neches-Sabine system these "Deweyville" paleomeander features are quite common. They occur as large depressions, evident from aerial and satellite images due to their distinctive topography, hydrology, soil, and vegetation patterns. The paleomeander depressions occur throughout the study area, though in the delta (reach 6) they are evident only on the valley margins due to burial by Holocene sedimentation.

Other Valley Features. Remnants of previous floodplain levels—alluvial terraces—occur throughout the lower Sabine valley, except in the delta where these features are buried. These are generally referred to as "Deweyville" terraces, though at three separate generations or alloformations are recognized. One to three terrace surfaces are evident at various points along the valley, roughly coincident with the generations of paleomeander features exposed, as outlined by Phillips (2008a; 2008b). The terraces are slightly higher and relatively drier components of the valley, except in the case of the youngest and lowest terraces, which may be only slightly higher than, or at the same elevation as, the modern floodplain.

Islands are semi-stable, vegetated land surfaces in anabranching reaches of the Sabine and its tributaries which are not inundated except during floods. These occur in the delta (reach 6), in conjunction with the multiple high flow channels in reach 5, and in some larger tributaries in reach 5.

Geomorphic interpretations of floodplain and valley GUs are summarized in Table 10; see Phillips (2008b) for more details.

Table 10. Geomorphic interpretation of floodplain and valley geomorphic units[a] (from Phillips (2008b).

Geomorphic Unit(s)	*Contemporary Processes*	*Geomorphic History*	*Possible Transformations or Changes*
Infilled abandoned channel	Vertical accretion	Avulsion and channel abandonment	Reoccupation by future avulsions (sand filled); inhibition of future avulsions (clay plugs)
Semi-active abandoned channel	High-water flow	Avulsion and channel abandonment	Infilling, or reoccupation by future avulsions or by tributaries
Anabranch	NA1	Valley aggradation & avulsion	Abandonment
Delta distributary	Deltaic sedimentation and divergent flow	Delta development	Abandonment; growth by flow capture
Alluvial distributary	Sediment and water dispersion to floodplain	Flood basin development plus avulsion	Abandonment; growth by flow capture
Billabong	Water storage	Avulsion	Infilling; reactivation by future avulsion or tributary occupation
Low-flow trib/ high-flow distributary	Influx to river at low flows; divergent fluxes from river at high flows	Tributary occupation of abandoned channels following avulsion	Infilling; conversion to tributary or distributary
Tie channel (batture)	Oxbow to river flux at low flows; opposite at high flows	Recent cutoff; crevasse channel cut to oxbow	Infilling; avulsion
Ridge-and-swale backswamp	Vertical accretion	Lateral channel migration	Burial by vertical accretion
Flat backswamp	Vertical accretion	Burial of ridge-and-swale; infilling of floodplain depressions	Alluvial terrace
Pleistocene meander scars/depressions	Infilling	Incision of pre-Holocene valleys formed during higher discharges	Infilling

Continued from	*preceding page*		
Cutoffs, oxbows	Infilling, water storage	Meander cutoff	Lakes to swamps to infilled
Natural levee	Ongoing or recent deposition	Overbank deposition	NA1
Crevasse splay	NA1	Levee breaching with decelerating sheet flow	NA1
Crevasse channel	High-water river to floodplain flow	Levee breaching with concentrated flow	Infilling; avulsion
Tributary channels	Water, sediment flux to river	NA1	NA1
Islands	NA2	Valley aggradation and anabranching; inheritance from Pleistocene anabranching	NA2
Alluvial terraces	NA1	Quaternary aggradation-degradation sequences	Burial of lower terraces; erosional dissection of higher terraces

[a]NA1: not applicable due to a large number of possibilities or complex relationships between forms, processes, and history. NA2: not applicable due to insufficient knowledge or information.

RELATIONSHIPS WITH INSTREAM FLOWS

The geomorphic units of the lower Sabine River valley occur at various elevations from the lowest points of the river channel to the margins of the valley. Accordingly, the GUs are inundated at various flow levels, which in turn influences their hydrologic functions, habitat characteristics, and rates and frequency of geomorphic change.

Five fundamental instream flow levels can be identified from a hydrogeomorphic perspective. The lowest, *thalweg connectivity,* is the minimum amount of discharge required to maintain continuous downstream water movement. *Bed inundation* is the flow level at which the entire channel bed is underwater and all mid-channel features are at least partially inundated. The *sub-bankfull* level is the higher range of flows that can occur before overbank flow begins. *Channel-floodplain connectivity* flows are those that result in river-to-floodplain flow via crevasse and tie channels, high-flow distributaries and anabranches, and tributary backwater flooding. Depending on local channel and levee morphology, this may occur at sub-bankfull levels. *Flood* or *overbank* flows are defined in this sense as those which result in levee overtopping.

Table 11 relates these flow levels to the geomorphic units inundated.

Table 11. Inundation of geomorphic units at various instream flow levels.

Thalweg Connectivity
Thalweg
Pools
Bed Inundation
All channel units except upper portions of marginal bars
Sub-Bankfull
All channel units
All bank-attached units
Channel-Floodplain Connectivity
Semi-active abandoned channels
Anabranches
Distributaries
Low-flow trib/high-flow distributaries/anabranches
Tie channels
Flood
All units except terraces and valley-wall fans (minor to moderate flood)
All units (major flood)

Chapter 3
Hydraulic Units

HYDRAULIC UNITS, HABITATS, AND BIOTOPES

Hydraulic units represent uniform patches of flow and substrate characteristics, and are related to biotopes and mesohabitats. Technical guidance for the Texas Instream Flow Program specifies that instream habitats will be delineated based on "mesohabitats" according to the following classification (TIFP, 2008: 69), one of several similar classifications often used in aquatic biology:

•*Pool:* flat surface, slow current, usually relatively deep.
•*Backwater:* flat surface, very slow or no current, usually out of main current.
•*Run/Glide:* low slope, smooth, unbroken surface.
•*Riffle:* moderate slope, broken surface
•*Rapid:* moderate to high slope, very turbulent.
•*Chute:* very high velocities in confined channel.

If the mesohabitat can be further discriminated, according to TIFP (2008), it should be assigned a qualifier for relative current velocity (fast/slow) and depth (shallow/deep). Notes are to be made on the location and density of woody debris and other instream cover, substrate composition, and presence of any unique habitat elements. Standards for terms such as fast, slow, moderate, high, low, etc. are not provided, but TIFP (2008: 69) does indicate that depth and current velocity measurements are to be taken "to facilitate objective criteria" in each sub-basin study (though no slope measurements are mentioned).

The mesohabitats referred to in TIFP (2008) are also called *biotopes*. Milan et al. (2010) reviewed five different biotope classifications from the river and aquatic sciences literature, none of which are identical to the TIFP classification—but all of which are quite similar, both to each other and to the TIFP mesohabitats. Beyond problems with imprecision and user variation in subjective classifications, various nomenclatures, and imprecise terminology (e.g., what constitutes a "deep" run?), Milan et al. (2010) identified several other issues with biotope classification. The links between the hydraulic biotopes and habitat have been questioned (Clifford et al., 2006; Shoffner and Royal, 2008; Milan et al., 2010). Biotopes are also stage-dependent. Little research has been done on the effects of flow levels or stage on biotope assessments, but observations show that stage-dependent changes clearly occur. For instance, areas that are riffles or rapids at moderate flows may become runs or glides at higher flows. Suggested qualifiers for the TIFP mesohabitats are also highly flow dependent, though the guidelines call for instream assessments to be made at discharges at or below median flow (TIFP, 2008).

While biotopes and mesohabitats are related to, they are not commensurate with hydraulic units. In large rivers, mesohabitats/biotopes are too large to represent uniform flow and substrate characteristics, one of the issues with biotope classification identified by Milan et al. (2010). It is precisely because biotopes do not represent uniform hydraulic conditions that their usefulness in describing habitat has been questioned by authors such as Clifford et al. (2006), Shoffner and Royal (2008), and Milan et al. (2010). For large rivers, hydraulic flow conditions may vary significantly by location within a biotope such as a "pool" or "run." Therefore, HU mapping provides a better understanding of the hydraulic complexity of biotopes and the habitats they represent. However, the identification of a biotope or mesohabitat, in combination with identification of substrate type and habitat elements specified by TIFP (2008: 69), is compatible in terms of scale of delineation with hydraulic units as used in a river styles framework. Thus the identification of HUs is consistent with the TIFP's instream habitat survey protocols.

METHODS

Hydraulic units were inventoried based on a combination of field observations, a database of continuous ground or river-level photography over much of the study area, low-altitude oblique aerial photographs, and high-resolution aerial photography.

The entire Sabine River and Old River channels from Burr Ferry to the Interstate 10 bridge was examined by boat at various times between 2005 and 2008; some reaches on multiple occasions. Continuous digital photography (i.e., photographs covering the entire river channel) archived by Copperhead Road Geosciences were analyzed to identify HUs. In addition, much of the reach from Toledo Bend Dam to Burr Ferry was also examined by small boat, canoe, or via land access in 2000-2001 and in 2006, with photographic records from those trips also available. Field notes from these previous observations were also utilized, which included detailed field mapping of specific cross sections, and general assessments of bed substrate and bank material, bank stability and vegetation, and the geometry and bedforms at tributary junctions. Measurements of bank height and channel width at selected cross-sections were made with a laser level, and of depth with a hand-held SONAR depth finder. The activity and stability of channel features was assessed on the basis of visible bedforms, vegetation cover, and evidence of downstream encroachment, lateral growth, or erosional diminution. Bank-attached and channel features were assessed on the basis of morphology, composition, and vegetation indicators of erosion-deposition processes and hydroperiod.

In October, 2007, in connection with studies of bars in the lower Sabine, several sections of the river were covered by boat in low-water conditions, with continuous photography of the channel using a GPS-enabled digital camera. This included the entire reach from Deweyville to the SRA-Texas canal, several reaches between Burr Ferry and Bon Wier, and several reaches between Bon Wier and Deweyville. Also in October, 2007, the river from Toledo Bend to Deweyville was flown during clear-sky, clear-water, low-flow conditions, and digitally photographed. This oblique photography was obtained from a variable altitude of <200 m (~600 ft); reduced-resolution examples are shown in figures 3 and 4.

In March, 2010, an 8 km reach upstream of Burr Ferry was reexamined by canoe to evaluate reported geomorphic changes in this zone. In this same period, a number of oxbows, cutoffs, sloughs, and paleochannels throughout the study area were examined by canoe to get more detail on HUs outside the main channel.

High-resolution (1 ft or 0.3 m) vertical color aerial photography from the U.S. Army Corps of Engineers was obtained, covering the study area from upstream of Bon Wier to Sabine Lake. This imagery was particularly useful in identifying floodplain and valley GUs difficult to observe in the field at such a broad scale. The photography was flown shortly after Hurricane Rita struck southeast Texas/Southwest Louisiana, making landfall in the Sabine Lake area, in September, 2005. This imagery was previously used to inventory tree blowdowns from the hurricane in the lower Sabine and Neches Rivers (Phillips and Park, 2009).

Figure 3. Low-level aerial photograph from October, 2007. The box shows cuspate bedforms on an extender type of connector bar.

Figure 4. Low-level aerial photograph from October, 2007. Shown is a linguoid bar formed due to constriction between two closely spaced alternate side marginal bars.

RESULTS

Hydraulic units are organized into mid-channel, channel-margin, point and lateral bar, and floodplain/valley HUs. The mid-channel HUs are, generally speaking, those that would be inundated by all but the lowest flows. The channel-margin units include the banks, and also HUs that are usually confined to the outer portions of the channel bed. HUs of point and lateral bars are treated separately from other channel margin units, and from those of mid-channel bars, which are included in the mid-channel HUs. The floodplain/valley HU inventory is less complete than the others, owing not only to the greater area to be covered and potential variety of host geomorphic units, but also to difficulties of field access and recognition of small features in the forested environment. However, the floodplain/valley HUs are of less significance to instream flow assessments and management.

In the tables below the general location of each HU within the channel/floodplain system is noted, along with the substrate. Where multiple substrates are listed, each constitutes a separate HU. For example, in the first row of Table 12, Outer Bed Sand and Outer Bed

Mud are separate HUs. Similarly, subtypes listed in the first column are separate HUs. Thus, for instance, in the fourth row of Table 12, there are three sand sheet HUs, according to whether the surface is plane bed, rippled, or with dunes. The geomorphic unit each HU is associated with is also indicated, along with the critical flow level necessary to inundate it. The keystone elements listed are key features required to create or maintain the HU.

Mid-Channel Hydraulic Units

HUs which occur within the main channel and are not confined to the edges or margins of the channel bed are shown in Table 12. In general, bed inundation flows are sufficient to activate these HUs, though in some cases flows approaching high sub-bankfull are required. Examples of some mid-channel HUs are shown in figures 5-14.

Figure 5. Portion of *Outer Bed* HU, exposed at low water.

Table 12. Mid-Channel Hydraulic Units of the lower Sabine River. Critical flow levels: TC = thalweg connectivity; BI = bed inundation; HBF = high sub-bankfull. A greater-than sign (>) indicates a flow higher than the indicated level is required, but less than the next higher level.

Unit	*Location*	*Substrate*	*Geomorphic Unit(s)*	*Critical Flow Level*	*Keystone elements*
Outer bed	Channel bed to bank transition	A. Sand B. Mud	Channel	BI	Channel
Central bed	Mid channel other than thalweg	A. Sand B. Mud	Channel	>TC	Channel
Thalweg	Mid channel	A. Sand B. Sand & gravel C. Mud	Thalweg	TC	Thalweg
Sand sheet A. Flat or plane bed B. Ripples C. Dunes	Mid channel	Sand	Sand sheet	BI	Sand sheet w/ flow regime to produce plane, ripple, or dune bedforms
Bar surface[1]: A. Flat a. rippled b. unrippled B. Convex a. rippled b. unrippled	Mid-channel bars	Sand	Mid-channel bars	BI	Mid-channel bars
Cross-bar channel	Mid-channel & lateral bars	Sand	Mid-channel & lateral bars	BI to HBF	Periodically exposed channel & channel margin bars
Thalweg pool	Channel thalweg	A. Sand B. Sand & gravel C. Mud	Thalweg	TC	Thalweg

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Shallow pool	Mid-channel above thalweg	A. Mud overlying sand B. Sand C. Algal mat overlying sand or mud	Between mid-channel bars	>TC	Mid-channel bars
Forced shallow pool	Mid-channel above thalweg	A. Sand B. Mud	Forced pool	>TC	LWD or other flow obstruction
Large woody debris (LWD)	Mid channel	A. Sand B. Mud	Channel, LWD	BI	LWD
Mud bar	Channel	Mud	Mid-channel Bar	>BI	Bedforms in fine-grained channels
Biotic mat	Channel	Algal or microbial film or veneer overlying sand	All bar types	BI to HBF	Exposed, temporarily inactive bar surfaces and depressions
Convex bedrock	Channel	Bedrock	Channel rock outcrop	BI	Exposed bedrock in channel
Bedrock pool	Channel	A. Bedrock B. Mud or sand veneer over bedrock	Channel rock outcrop	A. BI (lower positions) B. HBF (higher positions)	Exposed bedrock in channel
Meander pool	Channel	A. Sand B. Mud	Thalweg; Meander cutbank	TC	Meander
Prograding front	Channel	Sand	Mid-channel & tributary mouth bars	BI	Mobile bars
Cypress swamp	Channel	Mud	Oxbows, Sloughs, Anabranches	BI	Cutoffs, avulsions, seasonally-dry channels

Coastal backwater pool	Mid channel	Mud	Meander pool	TC	Deep meander pool

Figure 6. Low-water photo showing the *Central Bed* and *Thalweg* HU's inundated, with the Outer Bed and channel margin HU's exposed.

Figure 7. Portion of a sand sheet geomorphic unit. The HU in the foreground is *Sand Sheet-Plane Bed*, while the *Sand Sheet with Dunes* HU is in the background. A portion of a *Cross-bar Channel* HU is also shown.

Figure 8. *Thalweg pool* HU.

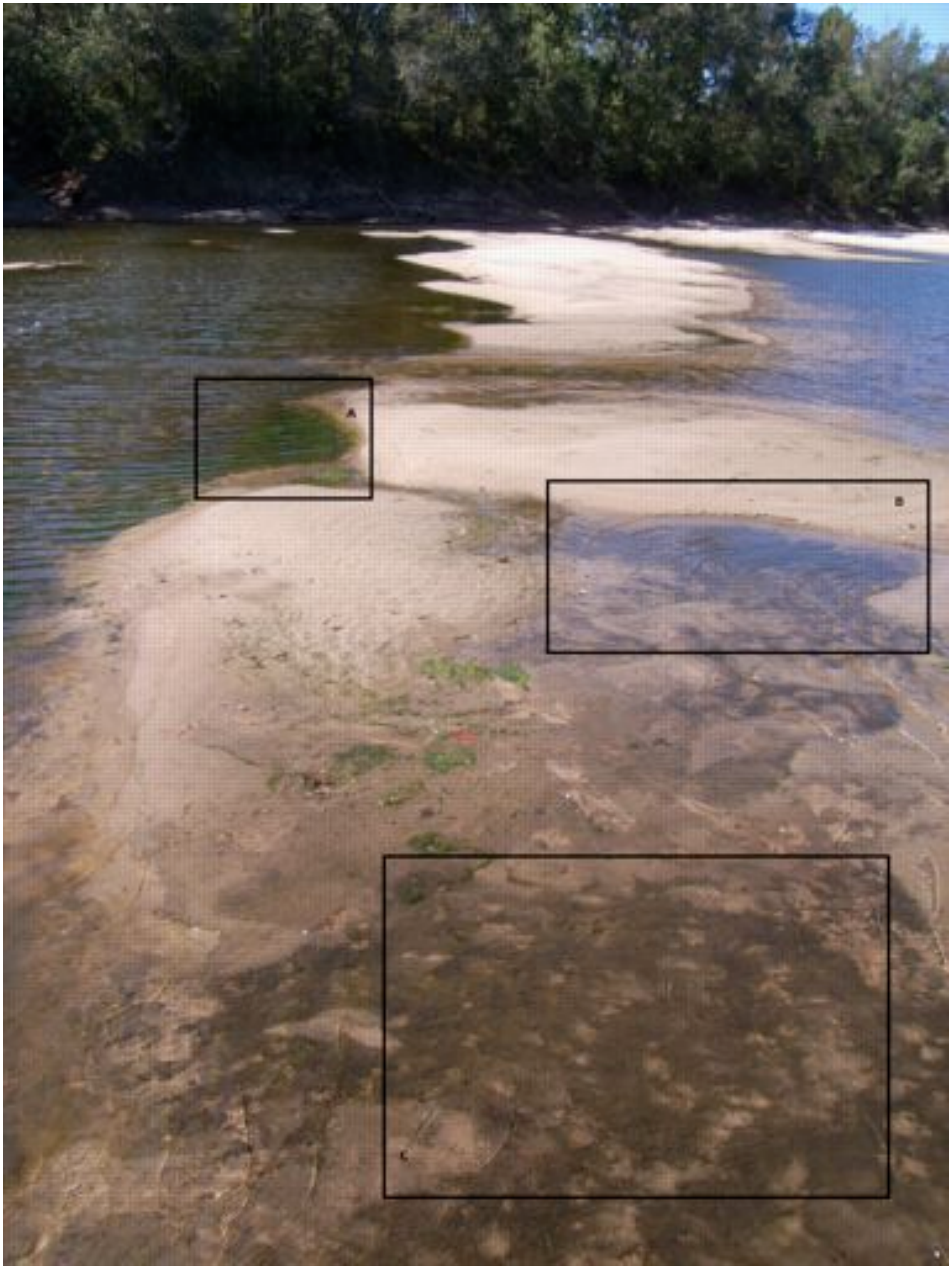

Figure 9. Connector Bar geomorphic unit, showing three different HU's: *Forced Shallow Pool* (A), *Shallow Pool* (B), and *Biotic Mat* (C). Photo taken at low water.

Figure 10. *Mud Bar* HU. These are not typically vegetated, but prolonged exposure during low flows in drought conditions allowed vegetation to become established here.


Figure 11. Rock outcrop showing the *Convex Bedrock* and the *Bedrock Pool* HU's.


Figure 12. *Meander Pool* HU.

Figure 13. *Prograding Front* HU

Figure 14. Blue Elbow, showing the *Coastal Backwater Pool* HU associated with deep circulator meander pool geomorphic unit.

Channel Margin Hydraulic Units

Channel margin HUs are associated with the edges or outer portions of the channel bed, with the banks, or with active or former tributary or distributary junctions. Units associated with bank-attached bars are treated separately in the next section. Flows of at least bed inundation level are required to activate all of these HUs. In some cases near-bankfull or overbank flows are necessary, as shown in Table 13.

Examples of some channel margin HUs are shown in figures 15-19.

Figure 15. *Unvegetated Convex Bank* HU, mud substrate.

Figure 16. *Vegetated Convex Bank* HU.

Table 13. Channel Margin Hydraulic Units of the lower Sabine River. Critical flow levels: BI = bed inundation; HBF = high sub-bankfull; FC = channel-floodplain connectivity; OB = overbank or flood. A greater-than sign (>) indicates a flow higher than the indicated level is required, but less than the next higher level.

Unit	*Location*	*Substrate*	*Geomorphic Unit(s)*	*Critical Flow Level*	*Keystone elements*
Unvegetated convex bank	Banks	Mud or cohesive soil	Convex bank	BI to HBF	Convex bank in fine-grained materials
Vegetated convex bank	Banks	Vegetated cohesive soil	Convex bank	HBF	Convex bank in fine-grained materials
Flooded forest	Tributary mouths; embayments	A. Mud B. Sand	Tributary mouth; various channel bank units	HBF	Bottomland hardwood trees (large woody hydrophytes)
Tributary mouth bar	Tributary mouths	A. Sand B. Mud C. Mud veneer over sand	Tributary mouth	BI to HBF	Tributary confluence
Unvegetated concave bank	Banks	A. Sand B. Cohesive soil	Concave or complex banks	>BI	Eroding bank
Channel plug	Confluences with abandoned channels	A. Sand B. Mud	Abandoned channels	HBF to FC	Cutoffs & avulsions
Bank overhang—root mat	Eroding banks	A. Cohesive soil B. Sand	Concave & overhanging banks	HBF	Dense root mats in cohesive sol on eroding banks
Large woody debris jam	Confluences with abandoned channels	Large woody debris	Large woody debris	HBF	Woody debris, cutoffs & avulsions
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Cypress fringe	Banks; channel-wetland transitions	A. Mud B. Sand	Cypress fringe	>BI	Bald cypress
Cypress stump fringe	Banks	A. Sand B. Mud	Cypress buttress	>BI	Cypress stumps
Recirculating eddy	Channel margin; tributary & distributary mouths	Mud and/or organic	Tributary & distributary mouths	>HBF	Backwater eddy circulation
Bank LWD	Banks	A. Sand B. Mud	Concave banks	>BI	LWD rooted or embedded in banks
Bank slump	Banks	Vegetated: A. Cohesive Soil B. Sand	Concave banks; slumps	HBF	Bank slope failures
Fringe marsh	Channel-wetland transitions	A. Mud B. Mud overlying sand	Marsh	>BI	Marsh
Bank rock outcrop	Banks	Bedrock	Bank rock outcrop	HBF	Exposed bedrock
Sand ramp	Banks	Sand	Sand ramp	HBF	Sand ramp

Figure 17. *Unvegetated concave bank* HU.

Figure 18. Concave banks featuring the *Bank Overhang-Root Mat* HU.

Figure 19. High-water view of the *Cypress Fringe* HU.

Point Bar and Lateral Bar Hydraulic Units

Lateral, and particularly, point bars are common in the lower Sabine River. These are often exposed at low flows, but flows ranging from high sub-bankfull to overbank inundate a number of HUs, shown in Table 14. These differ primarily according to their location on the bar and substrate, though some are also vegetated. Some examples are shown in figures 20-23. The lowermost, steeply sloping portions of such bars are considered outer channel HUs.

Figure 20. Point and lateral bar surface hydraulic units, including convex (A), flat unrippled (B), convex rippled (C), and concave/pool (D).


Figure 21. A (point) *bar surface gravel veneer* HU (left of photo).

Table 14. Point and Lateral Bar Hydraulic Units of the lower Sabine River. Critical flow levels: BI = bed inundation; HBF = high sub-bankfull; FC = channel-floodplain connectivity; OB = overbank or flood.

Unit	*Location*	*Substrate*	*Geomorphic Unit(s)*	*Critical Flow Level*	*Keystone elements*
Lower point bar mud veneer	Lower point bars	Mud veneer over sand	Point Bar	HBF	Low-slope point bar
Cross-point bar chute channel, vegetated	Point bars	A. Sand B. Mud overlying sand	Point Bar	OB	Point bar
Cross-point bar chute channel, unvegetated	Point bars	Sand	Point Bar	OB	Point bar
Point bar surface	Point bars	Sand	Point Bar	OB	Active sandy point bar
Point bar surface-mud	Point bars	Mud	Point Bar-mud	HBF to OB`	Fine-grained point bar
Vegetated point bar surface	Point bars	A. Sand B. Mud or cohesive soil C. Mud veneer over sand	Point Bar	OB	Stabilized point bar
Lateral bar surface (unvegetated)	Lateral bars	A. Sand B. Mud C. Biotic crust over sand or mud	Lateral Bar	HBF	Active lateral bar
Gravel veneer	Upstream end of point bars	Gravel & sand	Point Bar	BI to HBF	Gravel
Bar surface A. Flat a. rippled b. unrippled B. Convex a. rippled b. unrippled C. Concave/ pool	Point & lateral bars	Sand (A,B); sand or mud veneer over sand (C)	Point & lateral bars	HBF	Point & lateral bars

Figure 22. *Lower point bar mud veneer* HU (foreground). Point bar surface and vegetated point bar surface HUs are visible in the background.

Figure 23. *Vegetated Point Bar Surface* HU (right foreground).

Floodplain and Valley Bottom Hydraulic Units

Hydraulic units of valley bottoms and floodplains are, by definition, not normally subaqueous, and generally require channel-floodplain connectivity overbank flow levels for inundation. However, they can become important hydraulic elements and aquatic habitats during high flows. These elements are also important wetland and riparian habitats. The major HUs are listed in Table 15; some examples are shown in figure 24.

Table 15. Floodplain and Valley Bottom Hydraulic Units of the lower Sabine River. Critical flow levels: BI = bed inundation; HBF = high sub-bankfull; FC = channel-floodplain connectivity; OB = overbank or flood.

Unit	*Location*	*Substrate*	*Geomorphic Unit(s)*	*Critical Flow Level*	*Keystone elements*
Forested floodplain basin	Pleistocene meander scar depressions on floodplain	Fine-grained & organic soils	Deweyville meander scars	FC; OB[1]	Paleomeander depressions
Channel fill	Abandoned channels on floodplain	Mud	Abandoned channel	FC	Cutoffs & avulsions
Flooded riparian forest	Floodplains near channel margins	A. Sand B. Mud or cohesive soils	Floodplain backswamp	HBF; FC; OB	Depressional area behind natural levee
Floodplain cypress[2] swamp	Abandoned channels on floodplain	Mud	Oxbow, Slough, Anabranch	FC; OB[1]	Bottomland hardwood forest
Oxbow lake	Cutoff meanders on floodplain	Mud or mud overlying sand	Oxbow	FC[1]	Cutoffs
Slough (billabong)	Abandoned channels	Mud or mud overlying sand	Abandoned channel	FC[1]	Avulsions followed by channel abandonment
Oxbow swamp	Partially-infilled cutoff meanders	Mud & organics	Oxbow	FC to OB[1]	Cutoffs

[1]May also be inundated due to high water tables or local runoff.

[2]May include other bottomland hardwood tree species.

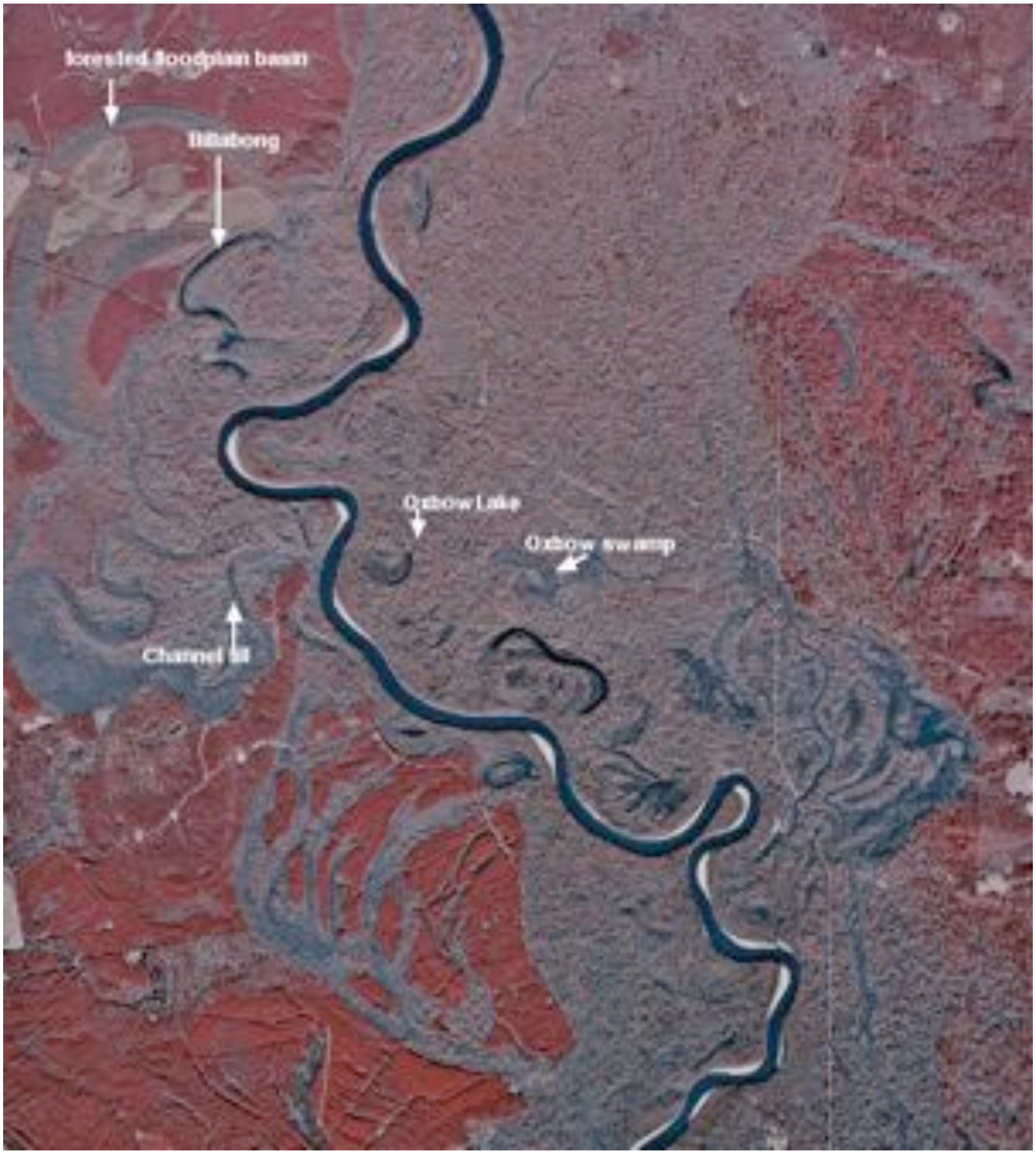

Figure 24. False-color DOQQ image of a portion of the Sabine River valley between Big Cow and Nicholls Creeks, showing the landscape setting of some floodplain and valley bottom hydraulic units.

New, Temporary, and Emergent Units

Hydraulic (and geomorphic) units are by nature, and to varying extents, variable, mobile, impermanent (or even ephemeral), and dependent on specific flow conditions. In addition, at time scales intermediate between the individual flow events that may create, destroy, modify, or relocate HUs and the longer-term historical and geological changes in fluvial systems, new geomorphic and hydraulic units may develop (and subsequently be removed).

Several examples were observed in the lower Sabine River in 2010. A period of relatively low flows and few large bankfull flow events (particularly upstream of Big Cow Creek) in 2005-2007 allowed vegetation to become established along some channel margin bars where, under more typical flow conditions, frequent inundation and substrate instability would inhibit vegetation establishment. These plants became well established enough to stabilize the features, which are likely to persist at least until a high-energy flood event occurs. These features may be submerged at less than bankfull flows, and represent distinctive habitats (figure 25).

Figure 25. This lateral bar upstream of the highway 63 crossing shows up as an unvegetated bar in 2004 aerial photos. This photo, taken in March, 2010, shows the establishment of vegetation and its inundation at a high sub-bankfull flow level. Emergent woody plants indicate establishment of most of the vegetation during the 2005-2007 low flow periods.

Other Hydraulic Units

Specific combinations of flow regime, substrate, and habitat elements occur in virtually endless variety in the lower Sabine River, and any other river system. The HUs identified above represent the most common and archetypal units in the study area, but detailed examination of any field site is likely to reveal exceptions which do not fit neatly into any of the types identified here. While floodplain and valley bottom units are included, the emphasis in this study was on the main, active channel. Thus more extensive examination of, e.g., oxbows, sloughs, and anabranches would certainly reveal more HUs. A suggested protocol for identifying new or variant HUs is as follows:

(1) Identify whether the new HU is a mid-channel, bank or channel margin, point or lateral bar, or floodplain/valley bottom feature.

(2) Relate the HU to a geomorphic unit, recalling that the size or extent of an HU must be less than or equal to that of a GU.

(3) Identify the substrate, in general terms (i.e., gravel, sand, mud, soil).

(4) Determine any keystone elements necessary to create or maintain the HUs.

(5) Determine the minimum flow level necessary to submerge the unit, relative to the five critical levels of thalweg connectivity, bed inundation, high sub-bankfull, channel-floodplain connectivity, and overbank.

(6) Choose a suitable descriptive name, with enough detail or modifiers to distinguish it from similar HUs.

Chapter 4
Hydraulic Units and Instream Flows

CRITICAL INSTREAM FLOW LEVELS

The tables in Chapter 3 indicate the key instream flow levels necessary to submerge hydraulic units, in terms of the critical stages of thalweg connectivity, bed inundation, high sub-bankfull, channel-floodplain connectivity, and overbank. These are summarized in figure 26, which shows the approximate sequence of HU submergence as stages increase from near zero to overbank floods. Owing to the various elevations or positions relative to the channel bed at which some HU's may occur, actual sequences in any given reach will vary from that shown in figure 26.

Note that floodplain and valley HUs are listed below point bar upper surfaces, which typically coincide with the morphological bank top elevation. This is because in much of the study area there exists high to very high channel-floodplain connectivity (Phillips and Slattery, 2007), and channel-floodplain connectivity flows typically occur below the bank top elevation and overbank flooding level. This occurs due to water distribution from the main channel in active and semi-active anabranches, backwater effects in tributaries, flow through crevasses in natural levees, and tie channels connecting oxbows and sloughs to the main channel (fig. 27).

Note also that floodplain and valley bottom HUs may also be inundated by ground water (local water table rise), direct precipitation and local runoff, and tributary inputs as well as river fluxes. Recognizing these multiple water sources, for purposes of managing instream flows with respect to floodplain and valley bottom HUs, four key stages may be identified. These include the channel-floodplain connectivity and overbank stages as defined earlier, and the valley flood and valley inundation stages. The valley flood stage is sufficient to inundate all the low points between the valley walls, including swales, billabongs, paleochannels, oxbows, paleomeander depressions, and other depressions. At this stage higher portions of floodplain and valley floor would still be exposed. The valley inundation stage is sufficient to submerge all topographic surfaces between the valley walls.

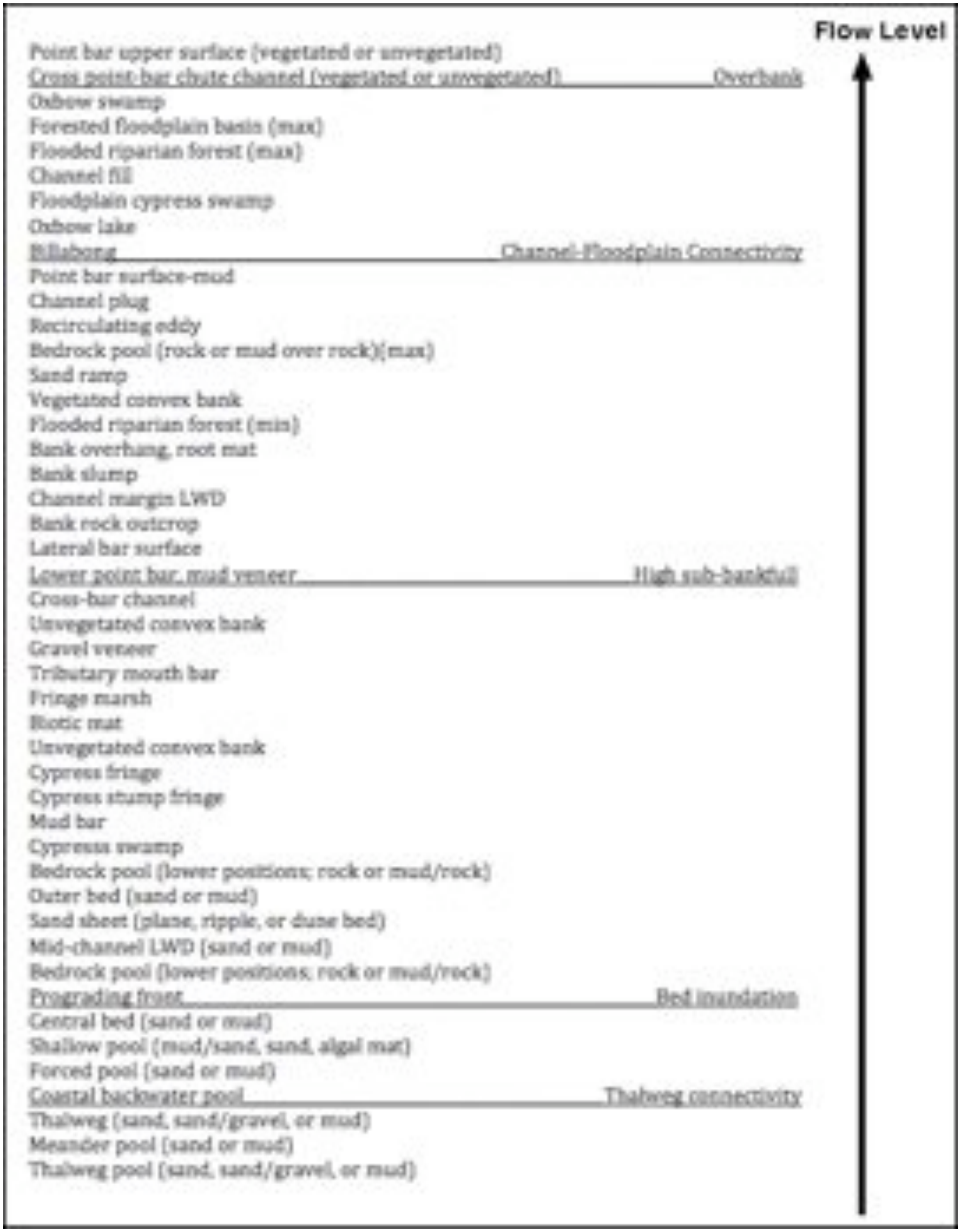

Figure 26. Approximate sequence of submergence of hydraulic units with flow levels ranging from near zero to overbank floods. The actual sequence will vary due to the range of elevations (relative to the channel bed) at which some units occur.

Figure 27. A tie channel connecting the Sabine River to an oxbow lake near Sudduth Bluff. Flow is away from the camera, from the river toward the oxbow. The channel bed of the tie channel is about 5 m above that of the river bed, so the tie channel conveys no flow except at higher than average discharges. The white line shows the approximate level required to overtop the river banks in this vicinity.

Valley inundation floods are rare. Downstream of the Burkeville gaging station, a stage of at least 115 ft (35 m) above sea level would be required to achieve this level. Given the datum of this gaging station (60.59 ft), a stage of about 54 feet would be necessary. The flood of record (in 1999) crested at just over 48 ft (14.6 m). In the vicinity of the Bon Wier gage, a water level of at least 80 ft (24.4 m) above sea level would be necessary to produce inundation of the entire valley in the vicinity, requiring a stage of nearly 47 feet. Only one stage above 40' (43.5) has ever been recorded at this site. Further downstream, however, in geomorphic zones 5 and 6, water levels less than 30 feet (9.1 m) above sea level are required. This implies a stage at Deweyville of nearly 36 ft, while the flood of record (1953) crested at <30', and the highest estimated flood pre-gaging station (32.2 ft in 1884) was also less than this level. Thus the valley inundation level can be treated as an upper limit, which will apparently only be exceeded in extremely rare events.

Hydraulic Units and Mesohabitats

As discussed in Chapter 3, the biotopes used as the first-order determinant of mesohabitats in the TIFP are not equivalent to HUs. Further, these hydraulic flow-based determinations are dependent on the discharge or stage. However, some general, approximate links between mid-channel, channel margin, and point or lateral bar HUs and the biotopes used in the TIFP (pool, backwater, run/glide, riffle, rapid) can be identified. These are shown in Tables 14-16.

Table 16. Relationships between mid-channel hydraulic units identified in chapter 3 and mesohabitat or biotope units.

Unit	*Mesohabitats or biotopes*	*Comments*
Outer bed	Pool, backwater, run/glide, riffle, rapid	More likely to be significant in pools, backwaters, and runs/glides. Mud substrate only in pools, backwaters.
Central bed	Pool, backwater, run/glide, riffle, rapid, chute	Mud substrate only in pools, backwaters. Chutes occur only locally on bedrock outcrops.
Thalweg	Pool, backwater, run/glide, riffle, rapid, chute	May be difficult to distinguish in riffles & rapids.
Sand sheet A. Flat or plane bed B. Ripples C. Dunes	Backwater, run/glide (flat or plane bed); riffle (ripple bed); riffle or rapids (dune bed)	Flow regimes and hydraulic mesohabitats vary greatly with flow, as does bedform state. Sand sheets may contain microscale biotopes at low water.
Bar surface[1]: A. Flat a. rippled b. unrippled B. Convex a. rippled b. unrippled	Run/glide (more likely for rippled surfaces); riffle (more likely for unrippled surfaces)	See chapter 2 and Phillips (2008b) for more detail on hydraulic and geomorphic relationships and characteristics of bars.
Cross-bar channel	Run/glide	Likely to be associated with broader-scale run/glide or riffle mesohabitats.
Thalweg pool	Pool	
Shallow pool	Pool, backwater	
Forced shallow pool	Pool, backwater	
Large woody debris (LWD)	Pool, backwater, run/glide, riffle, rapid, chute	More likely in riffles or backwaters.
Mud bar	Pool, backwater	Low-energy environments in zones 5 and 6 only
Biotic mat *Continued on*	Riffle, backwater *following page*	Forms when bar or bottom surfaces are exposed at low water, or subject to ponding

	Continued from previous page	
Convex bedrock	Riffle, rapid, chute	
Bedrock pool	Pool, backwater	
Meander pool	Pool	
Prograding front	Riffle	
Cypress swamp	Pool, backwater, run-glide, chute	Chutes occur only locally, and off the main channel
Coastal backwater pool	Pool, backwater	

Table 17. Relationships between channel margin hydraulic units identified in chapter 3 and mesohabitat or biotope units.

Unit	*Mesohabitat or Biotopes*	*Comments*
Unvegetated convex bank	Pool, backwater, run/glide, riffle, rapid, chute	Most common in run/glides, or locally associated with lateral bars.
Vegetated convex bank	Pool, backwater, run/glide, riffle, rapid, chute	Most common in run/glides, or locally associated with stabilized point or lateral bars.
Flooded forest	None	Riparian feature.
Tributary mouth bar	Pool, backwater	May have riffle, rapid, or chute-like characteristics with respect to tributary flow.
Unvegetated concave bank	Pool	May occur in other mesohabitats where banks are eroding, but mainly associated with meander pools on outer bends.
Channel plug	None	Pool or backwaters in the floodplain during high water.
Bank overhang—root mat	Pool, run/glide	
Large woody debris jam	Pool, backwater, run/glide, riffle	Most common in backwater, riffle.
Cypress fringe	Pool, backwater, run/glide	May be more appropriately considered a riparian feature.
Cypress stump fringe	Pool, backwater, run/glide	
Recirculating eddy	Backwater	Usually occur only at high flows.
Bank LWD	Pool, backwater, run/glide, riffle, rapids, chute	
Bank slump	Pool, run/glide	
Fringe marsh	None	Riparian feature.
Bank rock outcrop	Pool, run/glide, riffle, rapids, chute	May be more appropriately considered a riparian feature.
Sand ramp	Pool, run/glide	May be more appropriately considered a riparian feature.

Table 18. Relationships between point and lateral bar hydraulic units identified in chapter 3 and mesohabitat or biotope units.

Unit	*Mesohabitats or Biotopes*	*Comments*
Lower point bar mud veneer	Backwater	Low energy required for fine-grained deposition.
Cross-point bar chute channel, vegetated	None	Riparian feature.
Cross-point bar chute channel, unvegetated	Run/glide, chute	High flows only.
Point bar surface	Riffle	
Point bar surface-mud	Riffle	Fines deposited during relatively rapid stage decline.
Vegetated point bar surface	None	
Lateral bar surface (unvegetated)	Riffle	May occur adjacent to other mesohabitats.
Gravel veneer	Riffle	
Bare surface: A. flat (rippled or unrippled) B. Convex (rippled or unrippled) C. Concave/pool	Riffle (A, B); pool, backwater (C)	May exist only at higher flows.

Bed Mobility

The mobility of unvegetated hydraulic units can be assessed based on standard principles developed for studying bed load sediment transport and bed stability in alluvial rivers, which are reviewed by Church (2006).

Shear stress at any point in a river cross section (N m^{-2}) is given by

$$\tau = \gamma d S \qquad (1)$$

where γ is the specific weight of water, d is depth, and S the energy grade slope, often approximated as water surface or channel bed slope. The Shields number is a dimensionless measure of the ability of flow to entrain a particle of median diameter D (mm):

$$\tau^* = \gamma dS/g(\rho_s - \rho)\, D \qquad (2)$$

where g is the gravity constant and ρ_s, ρ are the densities of sediment particles and water, respectively (typically about 2.65 and 1.0 g cm^{-3}, respectively).

The lower Sabine River is of the type termed a "labile channel" by Church (2006). Labile channels (typically sand bed) experience full mobility over at least part of the channel bed. The threshold for particle motion is given by $\tau^* = \tau^*_{critical}$.

The critical dimensionless shear stress is a function of the particle Reynolds number Re_{p*}.

$$Re_{p^*} = (u\, D)/v \qquad (3)$$

where u is kinematic viscosity and v is velocity. This is estimated by replacing v with the shear velocity [= $((\gamma dS)/ \rho)^{0.5}$]. The critical conditions for sediment transport can then be estimated using the Shields Curve, as described by Church (2006).

Figure 28 shows values of depth and the Shields criterion computed for D = 1 mm (in the coarse sand range), and the mean and lower range of channel slopes in the study area. The threshold depth for entrainment is shown for each case. The interpretation of the relationship is that small flow depths are necessary to create mobility conditions—only about 0.11 m for the mean slope case, and 0.58 m for the low-slope case. Thus, even relatively low flow depths in most unvegetated mid-channel, channel margin, and lateral bar HUs is sufficient to result in mobility. These HU's should therefore be considered highly dynamic, and naturally subject to change and movement.

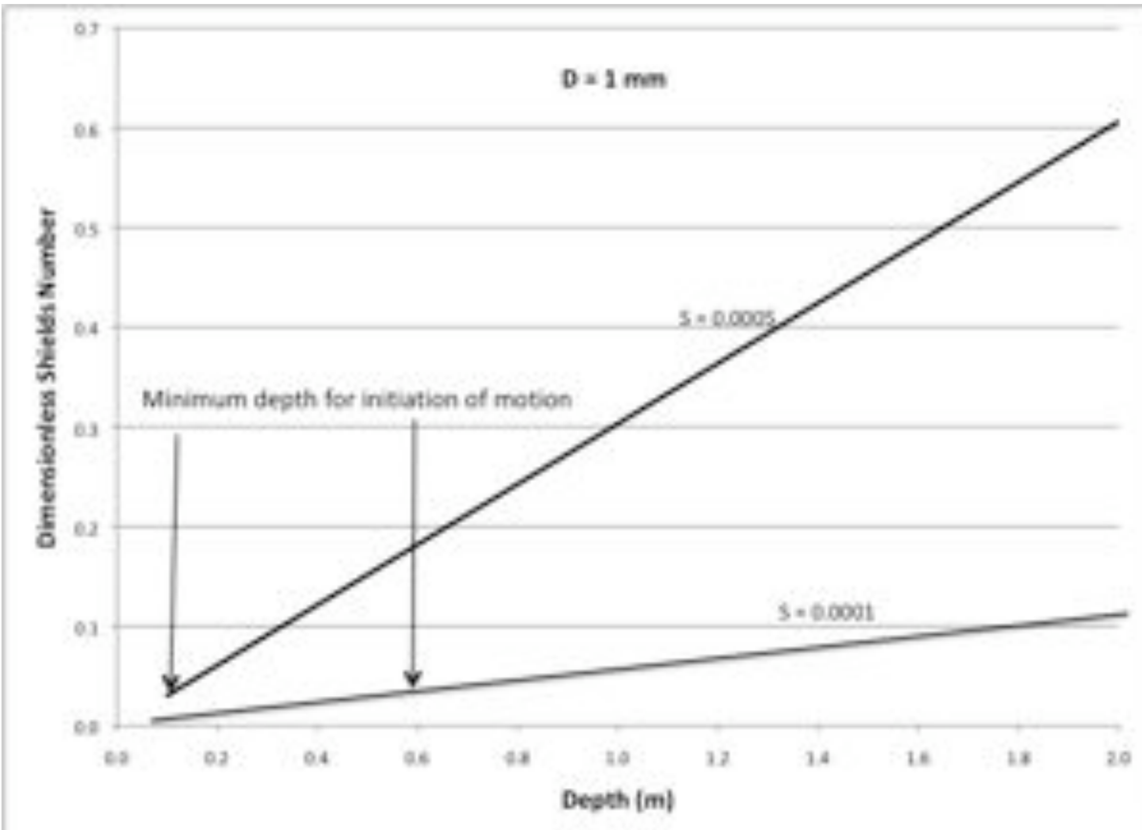

Figure 28. Relationship between Shields number and flow depth for slopes approximately equal to the mean slope of the lower Sabine River (0.0005) and for the lowest-slope river style reach (0.0001). Minimums for initiationof motion of a 1 mm sand grain are shown (assuming water temperature of 20º C).

Total sediment transport capacity is evaluated using stream power, the rate of work per unit time, which is related to shear stress. Power per unit bed width is

$$\omega = \tau_o V = \gamma R S V \tag{4}$$

where τ_o is mean boundary shear stress, *R* is hydraulic radius, and *V* is mean velocity. Cross sectional stream power is given by

$$\Omega = \omega w = \gamma Q S \tag{5}$$

with *w* = channel width at the flow surface. Power per unit weight of water (unit stream power) is the product of velocity and slope ($VS = \gamma Q S / \gamma A$; A = cross-sectional area).

Stream power—or any measure or index of stream sediment transport capacity—is most relevant to geomorphic change when compared to sediment supply. This is discussed further below.

CHANGES IN HYDRAULIC UNITS

Changes to hydraulic units may occur with respect to size (most often represented as area), spatial position, and character. Three qualitative types of changes in size can occur—persistence (no change), decline, and expansion. Indefinite decline, of course, ultimately results in the destruction of the HU. Spatial responses can be anchored (no movement), boundary-focused (expansion or contraction along the entire boundary), single-edge (e.g., on the up- or downstream boundary of the feature), or multiple-edge. Changes in character are considered in simplified form here as a binary—that is, modifications of, say, substrate composition, bedforms, morphology, etc. are not extensive enough to result in formation of a new HU, or a new HU is formed.

Figure 29 shows the possible generic pathways of HU change (including a no-change path). Persistent, untransformed HUs may be spatially translated, for instance downstream, but this must occur at more than one edge (but not the entire boundary). HUs that undergo a net decline may decrease in extent without being replaced by another HU, in some cases to the point of disappearance, when the process driving change replaces them with non-fluvial units (for example, natural or artificial fill, or introduction of anthropic structures). Otherwise, the declining HU's are transformed at one or more portions of their boundaries. Expansion of HUs, whether at one or more edges or around the entire boundary, must result either in the transformation of other HUs or non-fluvial features, or the spatial displacement of other HUs.

The inherent dynamism of all HUs, and the frequent mobility of most unvegetated units suggests that the persistent-anchored-untransformed pathway will be exceptional in most situations and over all but short time scales.

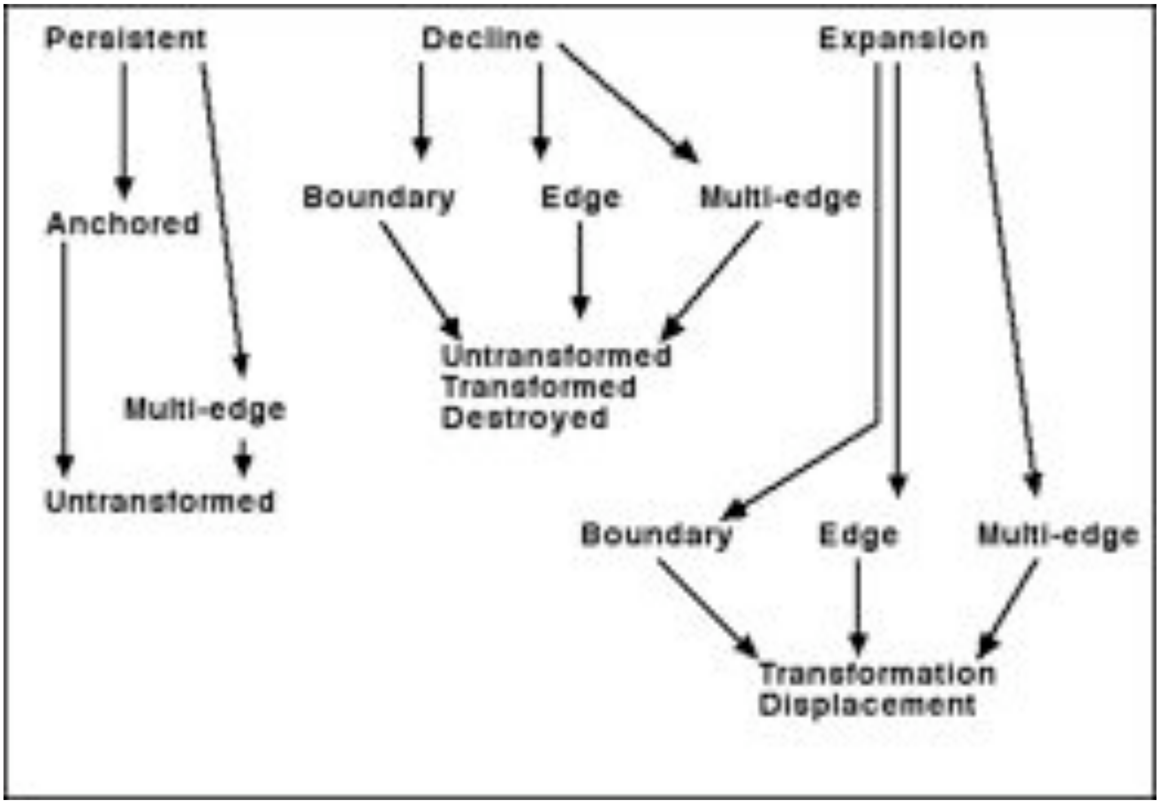

Figure 29. Possible generic pathways of hydraulic unit change. See text for explanation of terms.

Proximate Causes of Change

Ultimate causes or drivers of change in river systems include climate, sea-level, tectonics, land use, and water use, withdrawals and management by humans. The proximate causes of change in alluvial rivers such as the lower Sabine—that is, the manifestations within the river channel and valley of the ultimate causes—can be grouped into several categories: sediment supply/transport capacity ratio, lateral migration and sinuosity, avulsion, aggradation/degradation, base level, and channel evolution or metamorphosis. Discharge and slope are not listed separately because their product determines stream power and sediment transport capacity, as shown in eq. (5).

Changes to instream flows due to climate or human agency may result in increases or decreases in flows or flow variability and timing, changes in high and/or low extreme flows, and modifications to channel conveyance capacity (e.g., via dams, dredging, channelization). These modifications to flows are often directly or indirectly related to modifications of sediment supply. The most important direct influences of instream flow management is therefore manifest via the sediment supply/transport capacity relationship. Instream flow modification also directly effects base level where impoundments create local base levels. Because of the complex network of interrelationships in fluvial systems, however, indirect and knock-on effects may influence all the types of change listed above. The latter are discussed below, and their interactions in the following section.

Ratio between sediment supply and transport capacity. With respect to geomorphic change, modifications to discharge alone are less important than the changes to stream power, as an indicator of sediment transport capacity. This in turn is primarily relevant in the context of transport capacity relative to sediment supply. Changes in width, depth, channel slope, and sediment caliber may all occur (alone or in combination) in conjunction with changes in the ratio of supply and transport capacity. This is discussed in general terms in any fluvial geomorphology text of the past 30 years or so, and in the specific context of assessing fluvial response to human-induced changes by, e.g., Brandt (2000a; 2000b) and Phillips, et al. (2005).

Increases or decreases in transport capacity may be associated with changes in runoff or flow, modifications to energy grade slopes such as impoundments, and changes in channel roughness or resistance. Modifications of slope due to base level and planform change are considered separately. Alterations of sediment supply are usually driven by changes in climate or land use or by sediment trapping in impoundments, but can be associated with any factor that can affect erosion rates within channels or drainage basins.

Lateral migration and sinuosity. The lower Sabine River, like many alluvial streams, is characterized by active lateral channel migration. Migration is often associated with the growth of meanders and the combination of point bar accretion and cut bank erosion. Locally this must be accompanied by increases in sinuosity, or decreases when meander loops are eventually cut off. However, at the reach scale, it is possible for lateral migration to occur with no significant, persistent changes in sinuosity.

Increases in sinuosity have the effect of reducing slope and stream power (due to increasing stream length) and increasing the available space for mid-channel and channel margin HUs. Decreases in sinuosity (primarily due to meander cutoffs) increase slope and stream power and may decrease available channel space.

Avulsion. Avulsions are common in the lower Sabine and other Texas coastal plain rivers, and in many alluvial rivers more generally (Phillips, 2008). The outcome of an avulsion is an anabranch, a distributary, an active or semi-active subchannel, a billabong or slough, or channel fill (or, in a few cases, watershed fragmentation; Phillips, 2008). Thus avulsions create new floodplain and valley bottom geomorphic and hydrologic units, and may relocate and transform channel GUs and HUs. Because successful avulsions always occupy steeper paths than the original channel, avulsions are also related to lateral migration, sinuosity, and stream power changes.

Aggradation and Degradation. The Sabine and other Texas rivers have undergone several episodes of channel and valley aggradation and degradation over the Quaternary, resulting in formation of several sets of alluvial terraces. These episodes were driven by sea-level and climate change, but more spatially and temporally localized aggradation or degradation may be associated with pulses of sediment input, major floods, natural or human flow obstructions, or increases or decreases in stream power.

Base level. Regional changes in base level are associated with sea-level fluctuations and tectonic movements. Local changes may be related to impoundments or in-channel structures. Base level change influences fluvial processes via slope and stream power.

Channel evolution and metamorphosis. Channel reaches may undergo morphological and ecological changes due to internal interactions among fluvial system elements, independently of any external changes or forcings. In many cases, following a disturbance or change, or after channel initiation, channels undergo systematic changes over time analogous to ecological succession in vegetation communities. So-called channel evolution models describing these sequences are a common tool in river management and engineering (c.f. Bledsoe et al., 2002). Channel metamorphosis is a term describing complete alteration of channel form, either in response to hydroclimatic alterations, or to internal feedback mechanisms (Schumm, 2005).

CONCEPTUAL MODEL

The interrelationships among the types of fluvial change described above are shown in Figure 30. These represent the positive and negative links among system components. Positive links indicate that a qualitative change in one component produces a change in another component in the same direction (other things being equal). Thus, for example, an increase or decrease of stream power results in a corresponding increase or decrease in the stream power/sediment supply ratio. Negative links indicate that a change in one component induces, *ceteris parabus,* a change in another in the opposite direction. For instance, increased sediment supply produces a decrease in the stream power/sediment supply ratio, and vice versa.

Many of the links are self-evident. The links involving avulsions are discussed in detail, in the context of the Texas coastal plain, by Phillips (2008; 2010). The relationship between base level and sinuosity in coastal plain rivers is discussed by Schumm (1992). A few of the components in fig. 30 may have either positive or negative links connecting them. Lateral migration may increase sinuosity due to net meander growth and extension, or decrease it due to meander cutoffs. Base level rise or fall may either increase or decrease channel slopes, depending on the gradient of the coastal plain or continental shelf over which the sea is transgressing or regressing.

Self-effect loops are omitted from fig. 30 for clarity, but sinuosity, avulsion, and aggradation/degradation may all have negative self-effects. Sinuosity is limited at the upper end by greater frequency of cutoffs, and at the lower range by the tendency for alternate lateral bars to form. Avulsions are self-limited in the sense that once a channel shift occurs, near-future avulsions at the same site are highly unlikely. Aggradation may be self-limiting due to increasing elevations of accreting surfaces relative to flow levels, and degradation due to exposure of resistant clay layers or bedrock in the channel bed.

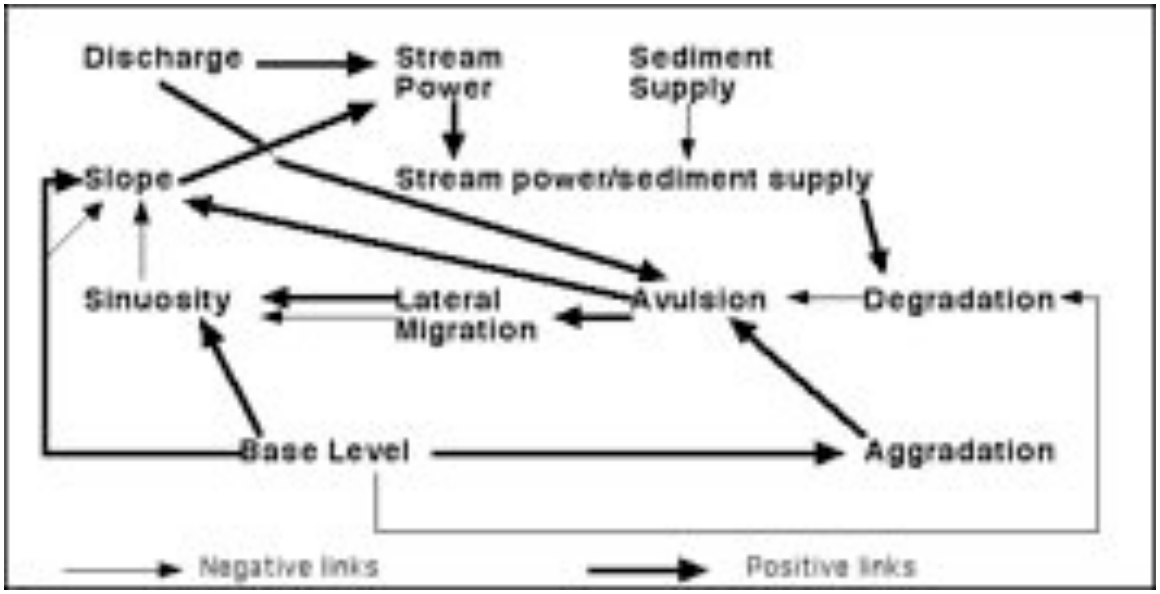

Figure 30. Relationships among discharge, sediment supply, and change mechanisms in sand-bed alluvial rivers. See text for explanation.

For purposes of determining the stability of systems such as that depicted in fig. 30, external forcings can be omitted—that is, components such as discharge and base level that influence, but are not directly influenced by, other system components. Likewise, pass-through components can be omitted (components with only one incoming and one outgoing arrow). This is *not* to say the omitted components are unimportant or insignificant; rather that their omission does not influence the system dynamical stability properties (Puccia and Levins, 1985; Logofet, 1993). Applying these rules, and including the self-effects, produces a system described by the interaction matrix shown in table 19. This is also the Jacobian matrix of the (nonlinear) dynamical system.

Table 19. Interaction matrix for Routh-Hurwitz stability analysis of the system in figure 30. Entries represent positive, negative, or zero effects of the row component on the column component.

	Slope	*Stream power*	*Degradation/ aggradation*	*Avulsions*	*Sinuosity*
Slope	0	a_{12}	0	0	0
Stream power	0	0	a_{23}	0	0
Deggradation/ aggradation	0	0	$-a_{33}$	$-a_{34}$	0
Avulsions	a_{41}	0	0	$-a_{44}$	$-a_{45}$

Sinuosity	$-a_{51}$	0	0	0	$-a_{55}$

Stability of the system can be determined by the Routh-Hurwitz criteria from the characteristic equation of the matrix:

$$\alpha_0\lambda_n + \alpha_1\lambda_{n-1} + \alpha_2\lambda_{n-2} + \ . \ . \ . \ + \alpha_{n-1}\lambda + \alpha_v = 0. \qquad (6)$$

The λ represent the eigenvalues, and $n = 5$ for the matrix in table 19. The Routh-Hurwitz criteria are both necessary and sufficient for dynamical stability. The criteria are that (1) all coefficients α are positive; and (2) all Hurwitz determinants are positive. This type of analysis is described in detail in standard texts on stability analysis of nonlinear dynamical systems (e.g., Cesari, 1971; Puccia and Levins, 1985; Wiggins, 1990; Logofet, 1993). Examples of specific application of these techniques in geomorphology, hydrology, and aquatic ecology include Slingerland (1981), Phillips (1990; 1991), Mendoza-Cabrales (1994), Dambacher et al. (2002; 2003), and Phillips and Walls (2004).

For the system of table 19, one coefficient of the characteristic equation is negative, and another is zero. The system is therefore dynamically unstable.

Dynamical instability indicates that the system is sensitive to minor variations in initial conditions, such that initial variations and irregularities tend to grow larger, on average, over time. In the context of the lower Sabine (and similar fluvial systems) this implies that the spatial pattern of GUs and HUs in a newly formed (or re-formed) section of channel (for example, created by an avulsion or intensively scoured by a large flood) would become increasingly complex and irregular over time.

Dynamical instability also indicates sensitivity to small changes or disturbances, so that their effects are disproportionately large and long-lived relative to the original perturbation. This applies to internal alterations within the channel system, and to externally-driven changes (including instream flows).

Implications

The implications for instream flow management of this conceptual model in particular and river management more generally are as follows:

•Changes, whether human-induced or "natural," may have disproportionately long-lived and large effects.

•Such changes are likely to have complex influences on river geomorphology. These are often manifested as multiple modes of adjustment, where adjustements to the same change, even at similar cross-sections or reaches, may occur in several qualitatively different ways (e.g., Phillips, 1990; 1991; Legleiter et al., 2003; Thoms and Olley, 2004; Phillips et al., 2005; Schumm, 2005).

•Specific prediction of effects of changes in instream flows on HUs and GUs will require detailed analysis on a case-by-case basis.

•There is no single normative "natural" or "equilibrium" fluvial response to changes in flow, or state or condition for fluvial systems. A range of conditions and states are possible, and none can be assumed to be dynamically stable in response to even relatively small natural or anthropic changes.

Chapter 5
Summary and Conclusions

Hydraulic units of the lower Sabine River were inventoried based on a combination of field observations, a database of continuous ground or river-level photography over much of the study area, low-altitude oblique aerial photographs, and high resolution aerial photography. For each unit the general location within the fluvial system, substrate, associated geomorphic unit(s), and critical flow level for inundation was identified. Keystone elements necessary to create or maintain individual HUs were also identified. These HUs are not equivalent to the mesohabitats or biotopes as described in TIFP (2008). However, the protocol in the latter for assessing mesohabitats could be used to identify HUs. A suggested procedure for identifying HUs is laid out at the end of chapter 3 of this report.

A total of 37 mid-channel HUs were identified (table 11, chapter 3). Some are restricted to particular geomorphic zones, while others occur throughout much or all of the study area. In most cases bed inundation flows are sufficient to submerge these features, but some require higher levels.

Channel margin geomorphic units support at least 28 HUs (table 12, chapter 3). With a few exceptions most occur in at least a scattered fashion throughout most of the study area. Discharges greater than the bed inundation level, and up to high sub-bankfull in some cases, are required to inundate these units. HUs associated with point and lateral bars were treated separately, with 17 units identified (table 13, chapter 3). In most cases higher flows are required to submerge the bar units, from high sub-bankfull to overbank flood levels.

The hydraulic unit inventory for floodplain and valley bottom environments was not as intensive as for those more frequently affected by instream flows. Ten common, extensive HUs were identified (table 14, chapter 3).

The relationships between the HUs and key instream flow levels are summarized in chapter 4 (see especially figure 25). An analysis based on the Shields Number shows that, for conditions typical of the lower Sabine, deep flows are not necessary for mobility of most HUs. Exceptions include the bedrock units, and vegetated HUs. For the latter, mobility is lower than for unvegetated units, but will vary widely depending on vegetation composition, density, vigor, and age or size. In general, results indicate that HUs should be viewed and treated as temporary, even ephemeral features, highly contingent on local conditions and specific flow events. The general types of changes in HUs are described in chapter 4. Even at a very broad level of generalization, at least 18 qualitatively different pathways of change are possible (figure 29, chapter 4).

Changes to instream flows—and other alterations or environmental forcings—are manifest within the river channel via can be grouped into several categories: sediment supply/transport capacity ratio, lateral migration and sinuosity, avulsion, aggradation/degradation, base level, and channel evolution or metamorphosis. These phenomena are interrelated, as shown in figure 30 (chapter 4). A stability analysis shows that this network of responses is dynamically unstable, indicating that changes may have disproportionately long-lived and large effects, and complex influences on river geomorphology. This conceptual model indicates that specific prediction of effects of changes in instream flows on HUs requires detailed analysis on a case-by-case basis. However, the model is also consistent with the idea that no single normative "natural" or "equilibrium" response to changes in flow should be expected. To the extent management for specific HUs is practiced, the focus should be on maintaining the dynamism and heterogeneity of the fluvial environment, rather than a specific mix of HUs in particular locations.

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Appendix: Scope of Work

SCOPE OF WORK PLAN

Hydraulic Units of the Lower Sabine River

Jonathan D. Phillips

June 2009

<u>Overview</u>

This work plan addresses a cooperative research study of the hydraulic units of the lower Sabine River, Texas/Louisiana from Toledo Bend Dam to Sabine Lake, from the perspective of instream flow management. Building on previous work delineating geomorphic zones or reaches (river styles) and geomorphic units, this study addresses the characteristic hydraulic units within those zones. Hydraulic units are ecohydrologic elements shaped by (and influencing) flow-sediment interactions, and providing the physical context for specific aquatic habitats and patch dynamics. The dominant (in terms of size, frequency of occurrence, and influence on hydrologic and ecological conditions) hydraulic units (HU) associated with in-channel geomorphic units will be identified, described, and related to hydrologic and geomorphic processes. HUs will be related to specific reference discharges, in terms of flow levels at which (a) the HU is inundated and (b) critical flows at which major changes or transportation/relocation is likely.

The specific objectives are to:

(1) Identify and describe HUs associated with geomorphic units identified in previous work (Phillips 2008b).

(2) Relate HU inundation to river stages associated with key reference flow levels and recurrence probabilities.

(3) Identify potential changes or disruptions to HUs such as hydraulic removal, dessication, or burial by sediments.

(4) Develop a conceptual model linking reference flows and effects on geomorphic units and HUs in the lower Sabine.

(5) Write a summary about the methods used in the Texas river style mapping scheme.

<u>Hydraulic Units</u>

This study will be conducted in the context of the River Styles framework (Brierley and Fryirs, 2005). The fundamental reach-scale units, river styles, are defined on the basis of similarities of channel and valley morphology, channel-floodplain connectivity, dominant hydrologic controls and regimes, and geologic and other constraints. The geomorphic zonation and river styles of the lower Sabine are described by Phillips and Slattery (2007) and Phillips (2008a). Geomorphic units (GU) are specific landforms within reaches, e.g. point bars, natural levees, riffle-pool sequences. Geomorphic units are erosional, depositional, or transportational landforms, referred to by Brierley and Fryirs (2005: 26) as “the building blocks of river systems.” Each GU represents a distinct form-process association. GUs are generally capable of significant change on the scale of ~1 year, but may range from ephemeral to persistent due to the episodic, threshold-dependent nature of geomorphic change.

Hydraulic units are the most detailed level in the RS scheme, comprising specific hydrological and ecological elements such as large woody debris, bedforms, aquatic vegetation, and individual flow obstructions or roughness elements. These are at least potentially capable of significant change over time scales of hours to months, but again may range from ephemeral to persistent. Hydraulic units generally comprise the basic habitat elements for aquatic organisms.

<u>Methods</u>

Examples of mid-channel geomorphic units (Table 1) will be examined in the field to identify relevant HUs. At least 10 examples of most GUs will be examined, though some (e.g., circular meander pool) are relatively rare. At each sample site field observations will be used to determine which GUs and HUs will be inundated or submerged at each of these reference flow levels:

1. Thalweg connectivity (minimum to keep continuous downstream water movement)
2. Low baseflow (minimum to fully inundate channel bed)
3. High baseflow (maximum sub-bank top flow)
4. Floodplain connectivity (flow necessary to activate flow into oxbows, sloughs, etc. and to backflood tributaries; may be less than bank top).
5. Flood stage

At selected sample sites full cross-sectional surveys will be conducted, along with water surface slope measurements. These will be used to relate reference stages to discharge (Q) using the Manning equation:

$$Q = (R^{2/3} S^{1/2})/n$$

where R is hydraulic radius (m), S is the slope, and *n* the Manning roughness coefficient, estimated using methods described by Arcement and Schneider (1984). These will be evaluated relative to flow duration and recurrence probability curves for the three U.S. Geological Survey gaging stations within the study area, at Burkeville, Bon Wier, and Deweyville (Ruliff), Texas.

Table 1. Mid-channel Geomorphic Units of the Lower Sabine River and their association with zones or river styles (see Table 2). Styles in italics indicate that the GU is significantly rarer than in the other listed styles. See Phillips (2008b) for examples.

Geomorphic Unit	River Style
Thalweg	1,2,3,4,5,6
Bedrock	
Mid-channel	1
Marginal	1
Cross-channel	1
Bars	
Marginal	
Point bar (normal and breached)	
Dominantly sand	1,2,3,4,*5,6*
Dominantly mud (fine-grained)	*5*,6
Lateral bar (normal and breached)	1,2,3,*4*
Tributary mouth (normal and breached)	1,2,3,4,5,6
Diagonal	1,2,3,*4*
Forced	1,2,3,4,*5,6*
Mid-channel	
Forced	1,2,3,*4,5*
Transverse (linguoid)	1,2,3
Compound	1,2,3
Longitudinal	1,2,3
Sand sheet	2

Connector	1,2,3,*4*
Pools	
Riffle-pool sequence	1,2,3,*4*
Circular meander pool	6
Forced pool	
Downstream	1,2,3
Backwater	*1,2,3,4,*5,6
Glide (run)	1,2,3,4,5,6
Large Woody Debris Jams	1,2,3,4,5,6

Table 2. Major reaches (river styles) of the lower Sabine River. Locations are in river distance upstream of Sabine Lake in kilometers (Sabine River Authority of Texas river mileages in *italics*). See Phillips and Slattery, 2007 for more details.

Reach	*Location*	*Distinguishing Characteristics*	*Primary Geomorphic Controls*
1 Toledo Bend to Burr Ferry	213-192 *146-131*	Incision, steep slope, bedrock control, valley constriction, low sediment loads, pulsed flows	Geologic framework; Toledo Bend Dam releases
2 Burr Ferry to Bon Wier	192-131 *131-91*	Active lateral migration, ubiquitous large point bars, wider valley, larger sediment load	Valley width; avulsion
3 Bon Wier to Big Cow Creek	131-103 *91-70*	Active lateral migration, ubiquitous large point bars, wider valley, larger sediment load; high floodplain/channel connectivity; low slope	Valley width; avulsion; neotectonics
4 Big Cow Cr. to Shoats Creek lower	103-79 *70-54*	Active lateral migration, fewer point bars, high floodplain/channel connectivity, low slope	Neotectonics; valley width; coastal plain paleogeography
5 Shoats Cr. to Cutoff Bayou	79-47 *54-29*	Few and finer-grained point bars, high floodplain/channel connectivity with multiple high flow distributary channels, high sinuousity, embayed tributary	Holocene sea level rise; geology & coastal plain paleogeography; Pleistocene stream capture

		mouths	
6 Cutoff Bayou to Sabine Lake	47-0 *29-0*	Rare point bars; distributary flow network; very high sinuousity; deltaic; tidal influence	Holocene sea level rise; tidal and coastal influences; Pleistocene stream capture

Particular attention will be paid to hydraulic units associated with meander pool GUs, with the idea that these may serve as references and central concepts for the relationships between flows, GUs, and HUs.

Products

The final report of the field work will include a comprehensive catalog of hydraulic units, linked to geomorphic units, and indentification of potential impacts (objectives 1, 3 above). The relationship between HUs and reference flows (objectives 2,3) will be presented in terms of the flows or stages at which each HU is subaerially exposed, inundated, and potentially negatively impacted.

The final report for the summary of Texas river styles mapping scheme (objective 5) will include general descriptions of each map scale and how its units are classified. For each reference scale, a "geomorphic zone" is mapped at a estimated management size.
Each unit has exposed, inundated, and potentially negatively impacted depending on flow conditions. The conceptual model of the scheme will be used to synthesize the information and guide potential application to other rivers. Examples will be given of the scheme from rivers that have been mapped.

Personnel and Responsibilities

TWDB will oversee the activities of the project and serve as contract manager. Dr. Jonathan Phillips/Copperhead Road Geosciences (University of Kentucky, but functioning as an independent contractor) will be principal investigator, with research assistants.

Tasks

(1) Synthesis, assessment, and analysis of existing data.
(2) Field data collection.
(3) Field data analysis and interpretation.
(4) Development of conceptual model.
(5) Produce reports.

Hydraulic units of the lower Sabine River

Draft-final report to the Texas Water Development Board

Contract number 1004831022

REQUIRED CHANGES

General Draft Final Report Comments:

1. Please correct the following typos:
    a. Page 1, "contract number 100001102" should be "contract number 1004831022."
    b. Page 9, 4th paragraph, "the produce of discharge" should be "the product of discharge."
    c. Page 14, 5th paragraph, "associated with diverging low" should be "associated with diverging flow."
    d. Page 19, 4th paragraph, "do not extent to the top" should be "do not extend to the top."
    e. Page 56, 2nd paragraph, "used in the TIFP (pool, backwater, run/glide, riffle, rapid)" should be "used in the TIFP (pool, backwater, run/glide, riffle, rapid) can be identified."
    f. Page 67, Table 19, "analysis of the system in figure 28" should be "analysis of the system in figure 30."
    g. Page 67, 3rd paragraph, "and *n* = 5 for the matrix in table 17" should be "and *n* = 5 for the matrix in table 19."
    h. Page 67, 4th paragraph, "For the system of table 17" should be "For the system of table 19."
    i. Page 70, 1st paragraph, "as shown in figure 28" should be "as shown in figure 30."
2. Please add lines to all tables in order to make them easier to read. This comment relates to Table 2 (page 11), Table 4 (page 16), Table 5 (page 17), Table 7 (pages 20-21), Table 8, (page 22), Table 10 (pages 25-26), Table 12 (pages 33-34), Table 13 (pages 43-44), Table 14 (page 48), Table 15 (page 50), Table 18 (page 60), and Table 19 (page 97).
3. On page 19, 1st paragraph, the report states that "Undercut banks, where a portion of the bank overhangs and shades the water—may be of particular interest for aquatic habitats." Please clarify if undercut banks are a sub-category of the geomorphic units provided in Table 6 (page 18) or their own separate

category. If they are a separate category, please include undercut banks in Table 6.

4. On page 28, please clarify that Hydraulic Units represent uniform patches of flow and substrate characteristics. In large rivers, mesohabitats/biotopes are too large to represent uniform flow and substrate characteristics, one of the issues with biotope classification identified by Milan et al. (2010). It is precisely because biotopes do not represent uniform hydraulic conditions that their usefulness in describing habitat has been questioned by authors such as Clifford et al. (2006), Shoffner and Royal (2008), and Milan et al. (2010). For large rivers, hydraulic flow conditions may vary significantly by location within a biotope such as a "pool" or "run." Therefore, a Hydraulic Unit mapping provides a better understanding of the hydraulic complexity of biotopes and the habitats they represent. Please state this important point more clearly in the document.
5. Figure 28 (page 62) needs more explanation. This figure appears to show that the lower the slope, the lower the flow depth required to move a 1 mm grain size particle. For a fixed grain size, the Shields number is equal to a constant times the flow depth times the slope. Intuitively, the lower the slope, the greater the flow depth required to move a particle. And, conversely, the higher the slope, the less the flow depth required to move a particle. These intuitive conclusions are seemingly contradicted in Figure 28. If Figure 28 is in error, please correct the figure. If Figure 28 is not in error, please provide additional description in the report as the result seems counter intuitive.
6. On page 64, 3rd paragraph, the report states "modifications to discharge alone are less important than the changes to stream power." This statement is a bit confusing, as it is impossible to change discharge without changing stream power. Please consider rewording the phrase. Perhaps the following would be sufficient: "modifications to discharge alone are less important than other changes that impact stream power."
7. Page 69, 5th paragraph, the meaning of the following sentence is unclear: "Changes to instream flows—and other alterations or environmental forcings—are manifest within the river channel via can be grouped into several categories: sediment supply/transport capacity ratio, lateral migration and sinuosity, avulsion, aggradation/degradation, base level, and channel evolution or metamorphosis." Please consider rewriting to clarify the meaning.

SUGGESTED CHANGES

8. On page 18, 3rd paragraph, the report states that "The units were identified primarily on the basis of profile (bank top to channel bed) shape." Please consider providing a figure showing the profile shape (in general) associated with each of the geomorphic units listed in Table 6 (page 18). This would greatly assist readers of the report who are not familiar with geomorphic classification techniques.

9. On page 65, 4th paragraph, the report lists several potential phenomena that may result in changes to base level. Please consider adding to this list channelization of rivers, which may significantly lower the base level for associated tributaries.

RESPONSE TO COMMENTS ON DRAFT REPORT

All corrections made and suggetions accepted and incorporated into final report except item 8, which would have required renumbering most of the figures, reformatting much of the document, and significantly delayed the final report.