# Geomorphic Processes, Controls, and Transition Zones in the Guadalupe River

Project Report for the Texas Water Development Board and Texas Instream Flow Program, TWDB contract number 0904831034

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FINAL REPORT
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# Chapter 1
# Background, Study Area, and Methods

## INTRODUCTION

This report conveys the results of a study of the geomorphology of the Guadalupe River, Texas, from its upper reaches in Kerr County to the Guadalupe River delta. The study was designed to delineate major geomorphic process zones; to identify major geomorphic controls; and determine the location and primary controls over key "hinge points" or transition zones.

The specific objectives in the project scope of work were to:

(1) Develop a baseline characterization of the condition and behavior of the Guadalupe River.

(2) Examine longitudinal (downstream) changes in flow processes and energetics, channel and valley morphology, and patterns of recent geomorphic change.

(3) Classify the Guadalupe (based on items 1, 2) into geomorphic process zones.

(4) Identify the primary controls—both contemporary and historic—of the geomorphic process zones.

(5) Identify the current location, primary controls over, and potential future changes in critical transition zones.

This work was conducted in the context of, and in conjunction with, the Texas Instream Flow Program.

Transition zones in river systems are often associated with direct geological controls such as lithology, structure, inherited topography and landforms, and transitions in geomorphological resistance. Fluvial and alluvial landforms and morphology also reflect changes associated with hydrology, land use, climate, and other factors. Transition zones therefore reflect both static (on human time scales) factors such as geological boundaries, and dynamic factors such as upstream or downstream propagation of effects of, e.g., sea level rise or water withdrawals. Geomorphic controls also include continuous (or at least chronic) phenomena such as deltaic sedimentation, singular events such as effects of major storms, and inherited features such as alluvial terraces.

Over long (Quaternary and longer) time scales, rivers respond chiefly to base level, climate, and tectonics. On historic and contemporary time frames, rivers are strongly influenced by shorter-term climate and hydrologic fluctuations, land use and vegetation change, and various human impacts. The drivers of change both influence, and are reflected by, fluvial geomorphology. Thus the identification of geomorphic controls on transition zones facilitates assessment of trajectories and probabilities of future changes and migrations in these critical locations.

River management necessitates some subdivision or classification of channels, networks, and watersheds. For practical reasons units must be of manageable size and complexity, but variations in hydrological, ecological, and geomorphological boundary conditions within and between fluvial systems need to be accounted for. An approach to categorization based on identification of key transition zones facilitates logical subdivisions, and is directly relevant to pinpointing potential “hotspots” of high resource value and vulnerability. Transition zones are also often sensitive indicators of changes triggered by, for example, climate, sea level, and land use change.

### *Geomorphology and River Zonation*

The most obvious variations within and between fluvial systems are geomorphological--characteristics such as channel width and depth, bank type and steepness, floodplain morphology, slope, bed and bank material, and valley wall confinement. Fluvial geomorphology also influences, and is influenced by, hydrology. Aquatic and riparian habitats are directly related to specific landforms and geomorphic processes (e.g., Perkin and Bonner, 2010; Robertson and Augspurger, 1999; Johnston et al., 2001; Moret et al. 2006). The widespread acceptance of geomorphology-based classification systems by ecologists, hydrologists, and water resource managers is evidence of the general realization of the critical role of geomorphic properties for essentially all aspects of river systems (Newson and Newson, 2000; Parsons et al. 2002; Brierley and Fryirs, 2005; NAS, 2005). Geomorphology is also critical to classification, delineation, and impact analysis of wetlands, and U.S. government agencies have adopted an explicitly geomorphic/hydrologic approach to wetland identification and characterization known as the Hydrogeomorphic Method (Brinson, 1993; Johnson, 2005).

Rivers typically exhibit systematic changes in the upstream-downstream direction, complicated by local spatial variability in forms, processes, and controls. However, due to thresholds, or to the presence of key environmental boundaries, distinct zones characterized by specific hydrological, ecological, and geomorphic characteristics can be identified--though the boundaries between those zones may be gradual and indistinct. Because of the interrelationships among geomorphology, hydrology, and ecology in river systems, such boundaries or transitions will have a geomorphic expression—and thus can be linked to geomorphic controls.

## STUDY AREA

The study area is the Guadalupe River from Kerrville to Guadalupe Bay (figures 1, 2).

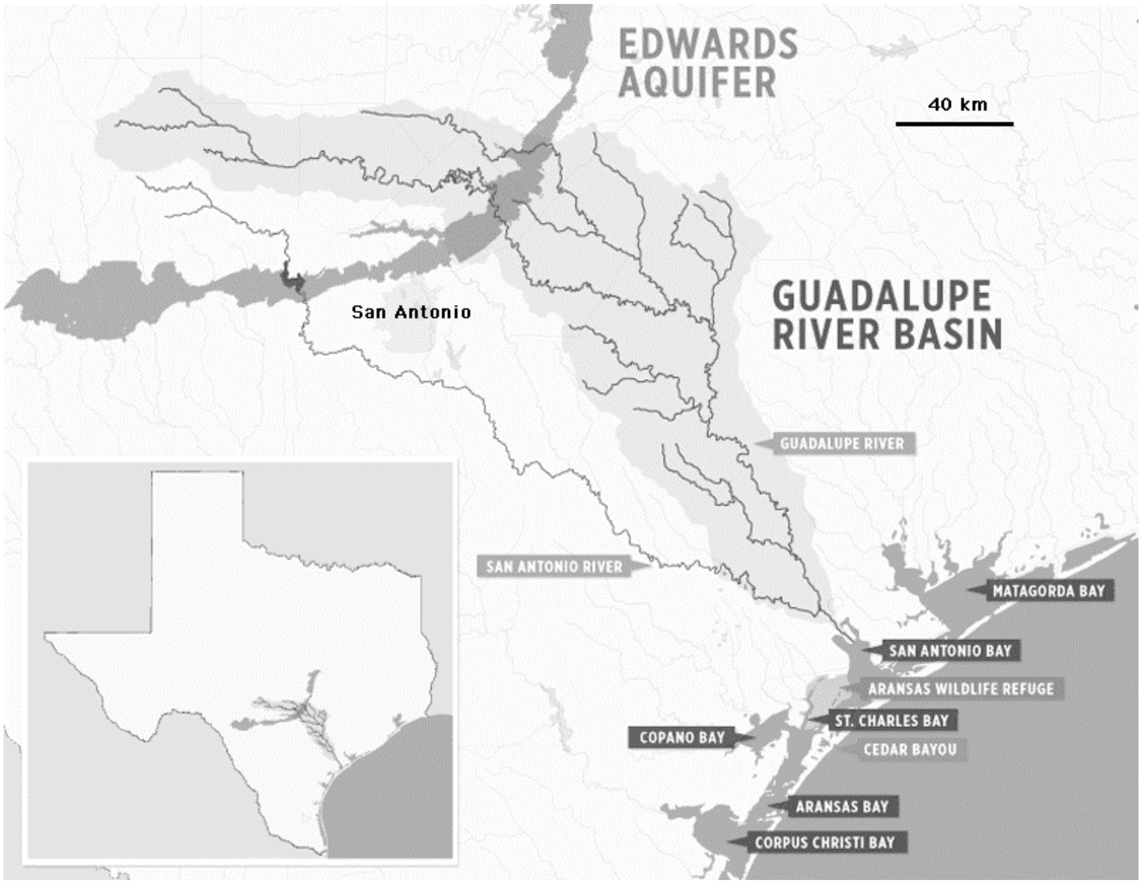


Figure 1. Guadalupe River watershed (excluding the San Antonio River) relative to the Edwards Aquifer and estuaries of the Texas Coastal Bend (adapted from a map produced by the Guadalupe-Blanco River Trust).

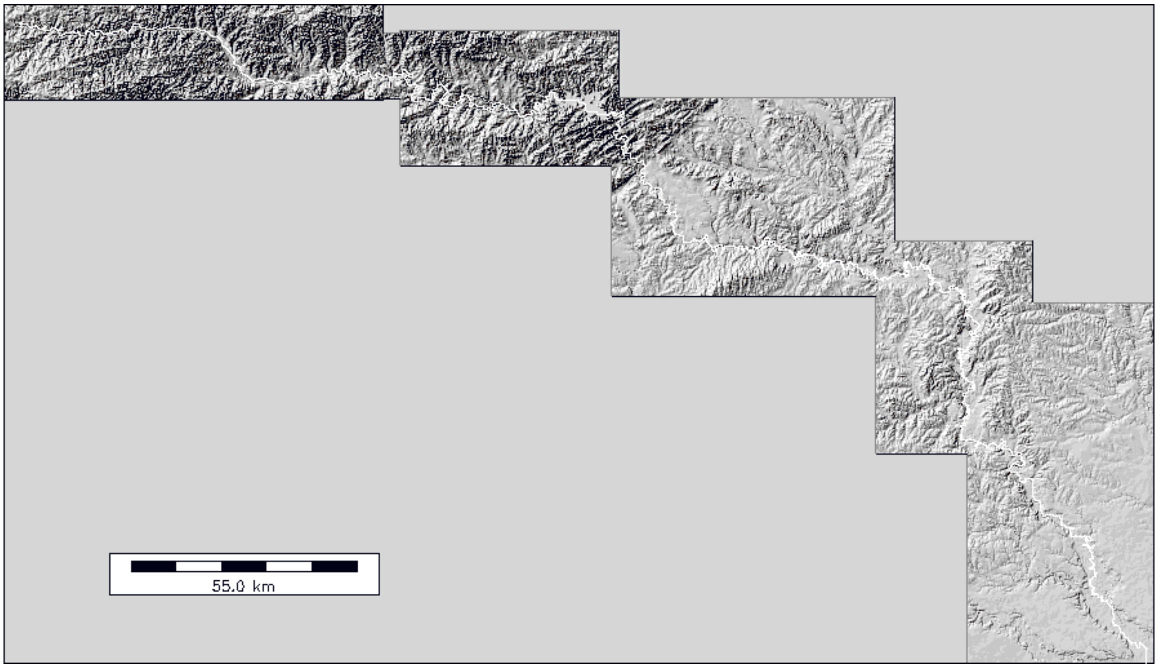

Figure 2. Shaded relief map of the Guadalupe River corridor.

The Guadalupe River valley passes through parts of six major land resource areas (MLRAs) as identified by the U.S. Department of Agriculture (USDA, 2006). The uppermost basin is within the Edwards Plateau-Central Part MLRA. Topography is characterized by plateaus and limestone hills, incised by deep valleys and canyons with flat valley floors. Lithologies are mainly limestones of Cretaceous age. Soils are predominantly Calciustolls and Haplustolls, with shallow versions on mesas, plateaus and hills, and very deep soils in valleys and on floodplains. Rock outcrops are common on hillslopes and at higher elevations. The Guadalupe flows through the Edwards Plateau—Eastern Part MLRA down to the Balcones Escarpment near New Braunfels. Geology, topography, and soils are similar to the central portion of Edwards Plateau, but precipitation is generally higher.

From New Braunfels down to approxmately Belmont, the Guadalupe passes through the Texas Blackland Prairie—Northern Part MLRA, which is within the western Gulf of Mexico Coastal Plain physiographic province. Topography is gently sloping except for dissected areas with steeper slopes along valleys in incised streams. Underlying geology of the uplands is mainly Cretaceous chalk, claystones, marl, and shale. Haplustert soils are found on uplands and stream terraces with high smectitic clay content, and Haplustolls and Calciustolls underlain by carbonate rocks. The river passes through a very small section of the Northern Rio Grande Plain MLRA, which in that portion is similar to the Blackland Prairie MLRA in terms of geology and topography.

The Texas Clayplan Area—Southern Part MLRA provides the environmental framework for the Guadalupe River from about Belmont (between Seguin and Gonzales) to near Cuero. Tertiary fluviodeltaic and marine formations underlie this area, including interbedded sandstones, siltstones, and shales as well as weakly or unconsolidated sediments. These occur in bands roughly parallel to the coastline. Topography is gently sloping, and incised by relatively narrow valleys. Dominant upland soils are Palustalfs, with Haplusterts where smectitic clay contents are high.

The lowermost Guadalupe River watershed is within the Gulf Coast Prairies MLRA. In the outer part of the western Gulf of Mexico Coastal Plain, topography is flat to gently rolling, with elevations generally below about 50 m. The geologic framework is Quaternary marine, coastal, deltalic, and alluviial sediments. Upland soils are dominated by Aqualfs and Udalfs.

Mean annual precipitation varies from about 500 to 800 mm in the Edwards Plateau MLRAs to 43 to 70 inches (1100 to 1600 mm) in the Texas Claypan and Gulf Coastal Prairies, with the Texas Blackland Prairie intermediate. Average annual temperatures are similar throughout the areas (about 68$^o$ F or 20$^o$ C), but mean freeze-free periods generally increase from the Edwards Plateau (250-275 days) down to the Gulf Coastal Prairies (>325 days).

Mean annual temperature at Victoria is 70$^o$F (21.1$^o$ C). The hottest month is August, with an average high of 94$^o$ F (34.4$^o$ C), and average low of 74 (23.4$^o$ C). The coldest month is January, when the average high is 63$^o$ F (17.1$^o$ C) and low is 42 (5.8$^o$ C). Mean annual precipitation is 37 in (950 mm). Precipitation falls throughout the year, with March the driest and September the wettest months, on average. In Kerrville the mean annual temperature is 68$^o$ (20 $^o$C). The hottest month (July) has average highs and lows of 92$^o$ (33.3$^o$ C) and 69$^o$ (20.6$^o$ C). The coldest month (January) sees average highs and lows of 58 and 32 (14.4 and 0$^o$ C). Mean annual precipitation is 31 in (800 mm), with precipitation occurring all year. Minima typically occur in winter, and maxima in late spring.

A number of small dams occur along the Guadalupe (Table 1). Most are low-head features that do not impound a large amount of water. A large dam, Canyon Dam, impounds Canyon Lake just upstream of the Balcones Escarpment west of New Braunfels. Canyon Dam was constructed primarily for flood control, but also serves as a water supply reservoir. The lake has a surface area of 8229 ac (33.3 km$^2$), and a conservation-pool capacity of 382,000 ac-ft (4.7119 X 10$^8$ m$^3$). Impoundment began in 1964.

Table 1. Impoundments on the main stem of the Guadalupe River. Some uncontrolled low-head dams are not included. Information from the GBRA.

| Name | Date | Location | Primary purpose | Volume[a] | Area[b] |
|---|---|---|---|---|---|
| Kerrville | 1980 | Kerr Co. | Water supply | 950[c] (0.0012) | 106 (43) |
| Canyon | 1964 | Comal Co. | Flood control | 382,000 (0.4712) | 8230 (3331) |
| Dunlap | 1928 | Guadalupe Co. | Hydroelectric | 5,900 (0.0073) | 410 (170) |
| McQueeney | 1928 | Guadalupe Co. | Hydroelectric | 5,050 (0.0062) | 396 (160) |
| Placid | 1928 | Guadalupe Co. | Recreation | 2,624 (0.0032) | 198 (80) |
| Nolte | 1931 | Guadalupe Co. | Hydroelectric | 1,550 (0.0019) | 153 (62) |
| Gonzales | 1931 | Gonzales Co. | Hydroelectric | 7,500 (0.0093) | 696 (282) |
| Wood | 1931 | Gonzales Co. | Hydroelectric | 4,000 (0.0049) | 229 (93) |

[a]At conservation pool or normal water levels, acre-feet ($km^3$).
[b]Acres (ha)
[c]At normal water levels. Maximum capacity is 2,499 ac-ft (0.0031 $km^3$)

## PREVIOUS WORK

### *Geomorphic Zonation in Texas Rivers*

Geomorphic characterizations similar to this study in purpose, scope, and methods have previously been developed for the lower Sabine, middle and lower Trinity, lower Brazos, and lower Navasota Rivers, Texas (Phillips, 2006; 2007a; 2007b; 2008). In addition to supporting needs of the Texas Instream Flow Program and other water resource management objectives, these assessments have been used to address geomorphic issues such as avulsion regimes, impacts of forest blowdown by hurricanes on fluvial systems, steady-state (or the absence thereof) in river longitudinal profiles, the influence of antecedent topography on modern fluvial systems, and effects of sea level and geological controls on river morphology (Phillips, 2007; 2008a; 2008b; 2010; Phillips and Lutz, 2008; Phillips and Park, 2009; Phillips and Slattery, 2008). A geomorphic classification for the lower San Antonio River was produced by Engel and Curran (2007), based on a more traditional statistical analysis of GIS data.

### *Guadalupe River Geomorphology*

In the vicinity of the Balcones escarpment, the Guadalupe and other rivers that cross the escarpment are prone to high-magnitude flooding—the incidence of such flooding is higher than any other area of the U.S. This phenomenon was addressed by Caran and Baker (1986), who identified a combination of climatological and runoff-response factors contributing to the high flooding potential. The Balcones escarpment region lies within a zone of convergence of polar air masses and easterly waves or tropical cyclones. A well-developed easterly wave approaching a lobe of high pressure, such as those often associated with a polar surge into middle latitudes, may produce strongly instability and heavy rains, as was the case, for example in the extreme floods that occurred on the Guadalupe River in 2002. Orographic effects associated with the escarpment topography can also enhance these rains (Caran and Baker, 1986). Nielsen-Gammon et al.'s (2005) climatological analysis shows that in general, exreme rainfall events in central Texas are associated with a northern deflection of the northeasterly trade winds into Texas, with deep southerly winds extending into the troposphere. This pumps abundant tropical moisture into the region with high potential for instability. Precipitation events producing more than 20 in (500 mm) of rain occur several times per decade in Texas (Neilson-Gammon et al., 2005). Earl and Dixon (2005) showed that the precipitation totals over four to 10 days for a 2002 storm in the region were more than double the published values for the "100-year" rainfall event, and suggested that traditional methods for assessing extreme precipitation and flood probabilites are inadequate for central Texas.

The topography and surface conditions result in a large and rapid runoff response to heavy rainfall events. Steep slopes, narrow valleys, thin soils (many with low infiltration capacity) over limestone bedrock, and relatively sparse vegetation cover result in high runoff and consequent stream discharges (Caran and Baker, 1986). Several other studies have confirmed the atypical flood regime of this area, and the general causal factors identified above (Baker, 1977; Patton and Baker, 1977; Alfinowicz et al., 2005; Curran et al., 2005). Recent work suggests a general pattern of increasing base flow discharge in Hill Country rivers such as the upper Guadalupe as grasslands formerly degraded by overgrazing convert to woodlands (Wilcox and Huang, 2010). Unusually high roughness or flow resistance values in rivers of the Edwards Plateau and Balcones escarpment such as the upper Guadalupe may contribute to flooding by reducing channel conveyance capacity (Conyers and Fonstad, 2005).

The thin soils of the Edwards Plateau are believed to be a legacy of Quaternary climate change. A combination of temperature, precipitation, and vegetation changes led to soil degradation, according to the reconstruction of Toomey et al. (1993). During the late glacial maximum and the latter stages of the most recent glacial period (about 20-10 Ka), the uplands had thick, reddish, clay-rich soils under open savanna vegetation. The transition to the Holocene climate resulted in reduced vegetation cover, and initiated soil erosion and truncation. The general phenomena identified by Toomey et al. (1993) have been confirmed by other studies in the region (see review in Ricklis, 2004).

Baker (1977; see also Patton and Baker, 1977) examined channel responses to floods in the Guadalupe and other central Texas rivers and developed a conceptual model of relationships between hydrologic characteristics of channels in flood, riparian vegetation, and channel morphology. Geomorphic and ecological effects of high-magnitude, low-frequency floods are greater and more persistent in the bedrock-channel streams of Central Texas than in fine-grained alluvial channels of humid regions, including the Guadalupe River further downstream.

Keen-Zebert and Curran (2009) studied characteristics of the mixed-bedrock/alluvial channels of a 87 mi (140 km) reach of the Guadalupe River in the Edwards Plateau area. They characterized the channel as a mixed or hybrid channel type, shallowly incised into bedrock and largely overlain by alluvial deposits. Examination of bar spacing, covering, grain size distributions, and downstream trends led Zeen-Zebert and Currran (2009) to conclude that the Guadalupe—and likely other rivers—in the study area behave as a distinctive channel type where both bedrock and alluvial processes operate in a spatially variable pattern of relative importance. Alluvial and bedrock channel reaches in the upper

Guadalupe are similar with respect to the distribution of gravel bars, surface grain size distributions of bars, and channel slope and width. Keen-Zebert and Curran (2009) proposed that the upper Guadalupe system has adjusted to changes in base level associated with the Balcones Escarpment Fault Zone by episodic incision into alluvial sediment and the underlying bedrock, essentially shifting from a fully alluvial river to a mixed alluvial-bedrock river.

The interaction of fluvial and karst processes and of surface and subsurface drainage systems in the Edwards plateau area was outlined by Woodruff and Abbott (1986). Fluvial drainage basins and aquifers have co-evolved. In the context of broader structural geologic and climatic controls, geomorphic development near the Balcones fault zone influenced the magnitudes and locations of recharge and discharge in the Edwards Aquifer (Woodruff and Abbott, 1986). Development of aquifers and ground water drainage influenced the evolution of surface drainage networks by both flow diversions (aquifer recharge) and stream flow augmentation via spring discharge. Woodruff and Abbott (1986) suggest that these phenonomea are mainly accounted for by stream piracy in the Guadalupe and San Antonio River basins.

Geomorphic research downstream of the Balcones escarpment is more limited. The lower San Antonio and Guadalupe Rivers were among the examples used by Ouchi's (1985) studies of the response of alluvial rivers to slow active tectonic movement. A tectonic feature, the post-Vicksburg flexure, crosses both rivers near the apex of their respective deltas. Ouchi (1985) attributes changes in river slope and sinuosity to effects of the tectonic subsidence.

Though discharge of the lower Guadalupe River is highly variable and increases downstream, Morton and Donaldson (1978) found that sand content of bed sediments, mean grain size of bed material, channel and valley gradients, sinuosity, and channel width/depth ratios all decrease downstream. They found the most pronounced changes at the transition from the alluvial plain to the Guadalupe/San Antonio River deltaic plain. Morton and Donaldson (1978) also provided detailed descriptions of flow patterns, sediment characteristics, and morphology of the delta system.

Development of the Guadalupe delta over the Holocene was reconstructed by Donaldson et al. (1970). The delta is part of a complex of lagoonal and deltaic deposits, slowly prograding into San Antonio Bay. Alluvium is deposited in a shallow, low-energy water body, and as the delta progrades into shallower water, distributary channels have cut below the level of the modern bay floor. Donaldson et al. (1970) argued that the Guadalupe delta has a distinctive style, characterized by: (1) fluvial water and sediment discharge which dominate weaker waves and currents of the bay; (2) shallow-water deposition such that waves can rework the deposits; (3) river channels incised below the bay floor; (4) progressive shallowing of the bay due to delta progradation; and (5) growth by development of a series of subdeltas, with most of the inactive subdeltas presently deteriorating.

## METHODS

### *Data Sources*

The identification of transition zones and potential geomorphic controls was made using a geographical information system (GIS) analysis of digital elevation and geologic data, aerial photography, and topographic maps. Analysis of discharge from gaging stations was also included (see chapter 2), along with field observations at a number of locations throughout the study area.

Digital elevation data (DEMs) at a 10 m resolution was extracted from the NED (National Elevation Dataset) from the U.S. Geological Survey. Digital ortho quarter quads (DOQQs), 1-m resolution color aerial photography taken in 2004, were obtained from the Texas Natural Resources Information System (TNRIS), as were digital line graph versions of 1:24,000 scale U.S.G.S. topographic maps. Geologic maps at a 1:250,000 scale, from the Geologic Atlas of Texas (GAT), were also downloaded from TNRIS. Discharge data was obtained for 12 gaging stations from the USGS, and information on flood levels and discharges from the Advanced Hydrologic Prediction Service (AHPS) of the U.S. National Weather Service.

The DEMs were transformed into density map form for visual analysis, and the DEM, DOQQ, DLG, NHD, and GAT data were taken into ARC GIS (ESRI, Inc.) and rectified for overlay and other analyses. The DEM data were also analyzed using RiverTools (Rivix, Inc.), a geomorphic and hydrologic analysis and modeling tool.

### *Boundary Criteria*

Potential geomorphic controls and indicators were identified from preliminary data analysis, and experience in similar work on the Trinity, Sabine and Brazos Rivers (Phillips and Slattery, 2007; Phillips, 2006; 2007a; 2008a; 2008b). These were then evaluated with respect to their relevance in the Guadalupe River system, and their usefulness in distinguishing geomorphic zones in the study area. Three criteria used in previous studies were not found to be useful. The presence of rounded gravels, a useful marker in the Sabine and Trinity Rivers, has little discriminatory power in the Guadalupe, as such gravels are present in the river channel throughout the entire river upstream of the Guadalupe River Delta (figure 3). The presence and density of sandy point bars was also not used, as these are less common than in the rivers further east, and provide no additional information on geomorphic processes or controls. A third criterion, the presence of distributary channels, occurs only in the delta area of the Guadalupe. A criterion not used in earlier studies, the source of streamflow and presence of man-made flow obstructions, was used in this project. The Guadalupe River experiences karst flow and spring inputs which do not occur within the study areas of earlier geomorphic zonation projects, and is more strongly influenced by dam releases. Further, there are a number of small dams along the Guadalupe River not found on the lower Sabine, Trinity, Navasota, or Brazos Rivers.

Figure 3. Cutbank and edge of a point bar on the Guadalupe River in Victoria. Note the rounded gravels evident in the lower foreground.

Seven criteria were therefore selected for boundary coincidence analysis (BCA): slope, sinuosity, valley width, valley confinement, geology, channel-floodplain connectivity, and flow regime. The study reach was then subdivided on the basis of each of these. The colocation or coincidence of boundaries based on two or more criteria is a likely indicator of a key transition point or zone. These key points identified from the BCA provide a starting point for the geomorphic zonation. No effort was made to identify reaches less than 5 km (3 mi) in length, in consideration of the >700 km (435 mi) length of the study area, and the purpose of the zonation. Note that for location-specific problems significant variations within zones shold be considered.

The criteria are briefly defined below.

*Slope* is the channel slope, and was measured from calculated channel paths in the DEM. Comparison of the DEM based flow path with DOQQs confirmed the accuracy of the former, at least for the main river channel.

*Sinuosity* is a measure of the "curviness" of the river, and is the ratio of straight-line of valley distance between two points, and distance along the channel path. Beyond being a distinctive geometric characteristic of rivers, sinuosity changes in coastal plain rivers often represent different forms of adjustment to base (sea) level change. In response to sea level rise or fall, coastal plain streams with limited capacity to degrade or aggrade their channels can adjust the hydraulic slope by increasing or decreasing the channel length. Zones of varying sinuousity were identified visually from DOQQs, and the sinuosity was calculated from DEM data using RiverTools.

*Valley Width* is based on the mean valley wall-to-wall width, and the ratio of maximum to minimum width. Valley walls in the study area are readily distinguishable as steep scarps, and are also reflected by geological boundaries between modern alluvium and/or Quaternary terraces and older formations. Both mean width and variability of valley width were considered.

*Valley Confinement* reflects the extent to which the channel is in contact with the valley walls. Following geomorphic convention, unconfined (UC) means that less than 10 percent of the channel length is in contact with the valley wall, and confined (C) that 90 percent or more of the length is pinned to a valley wall. Intermediate cases are partly confined (PC). In some cases more than one category was listed, due to distinct subreaches within broader reaches.

*Geology* indicates the dominant age of the formations bounding the river valley for the variety of Cretaceous, Paleocene, Eocene, Miocene, Pliocene, and Quaternary formations.

*Connectivity* denotes channel-floodplain connectivity and is a qualitative assessment (very low to very high) based on frequency of overbank flow as determined from gaging station data; presence and density of oxbow lakes, sloughs, and active subchannels and their proximity to the active channel; and morphological evidence of hydraulic connections between the active channel and valley features. Network characteristics with respect to convergent or divergent connections between the trunk stream and tributaries (or distributaries), and single- vs. multi-thread channel patterns was a significant distinction only in the lowermost Guadalupe River and delta area.

*Runoff and flow* regime refers to the major sources of stream discharge (karst/spring flow, fluviokarst runoff, non-karst runoff, Canyon Dam releases, tides) and the extent of flow influences of dams and barriers.

# Chapter 2
# Flow Regimes

## SOURCES OF STREAMFLOW

The upper Guadalupe River in the Edwards Plateau area and along the Balcones Escarpment is a fluviokarst system. Discharge of karst ground water along the escarpment is an important source of stream flow for the river downstream. Chief among these are Comal Springs in New Braunfels, the source of the 5.5 km (3.4 mi) long Comal River, and San Marcos Springs, source of the San Marcos River, which joins the Guadalupe near Gonzales. Canyon Lake is impounded just above the escarpment. Thus the sources of streamflow in the lower Guadalupe can be partitioned into four major inputs: Canyon Lake releases, Comal Springs, San Marcos Springs, and surface runoff and baseflow from the watershed below the escarpment. The Guadalupe-Blanco River Authority regularly tracks sources of flow at the gaging station at Victoria, by expressing lake releases and San Marcos and Comal springs discharges as percentages of discharges at the Victoria gaging station, with the remainder characterized as "natural baseflow" (http://gbra.org).

The U.S. Geological Survey (USGS) and the Edwards Aquifer Authority studied streamflow gains and losses and the relative contribution of flows from Comal, San Marcos, and Hueco Springs, the latter near the Guadalupe River downstream of Canyon Dam (Ockerman and Slattery, 2008). For a two-decade period (1987–2006) and several short-term periods (January 1999, August 1999, August 2000, and August 2006) the ratio of flow from the major springs (measured at the spring source) to the sum of inflows (measured at the source of inflow to the river system) was computed for reaches of the Comal River and San Marcos River that include springflows from major springs, and for Guadalupe River reaches downstream from Canyon Dam. This ratio is an estimate of the contribution of flows from major springs to streamflow. For 1987–2006, the springs accounted for, on average, 27 percent of the Guadalupe River flow at Gonzales, and 18 percent of the discharge in the Guadalupe delta area. At the lowermost reach, Canyon Lake releases accounted for 20 percent of river flow (Ockerman and Slattery, 2008).

Spring flow contributions are predictably greater during lower flow periods. For the short-term study periods of August 2000 and 2006 (periods of relatively low flow), springs accounted for 77 and 78 percent, respectively, of the inflows in the reach from below Canyon Dam to Gonzales, and 52 to 53 percent in the lowermost reach of the Guadalupe River. During these low flow periods the ratios of Canyon Lake releases to the sum of inflows were less than 10 percent (Ockerman and Slattery, 2008).

Perkin and Bonner (2010) found that the number of small and large floods increased slightly (from about 0.81 to 1.07 per year) in the upper Guadalupe River following impoundment of Canyon Lake in 1964, and decreased by about half (0.84 to 0.42 floods per year) downstream of the lake. The downstream change is to be expected, given the flood control function of Canyon Lake. However, given the slight increase in the upper river, and a small decrease in floods per year in the San Marcos River, factors other than the impoundment appear to account for some of the decline in the lower Guadalupe noted by Perkin and Bonner (2010).

GAGING STATIONS

The USGS and cooperating agencies maintain 13 gaging stations on the Guadalupe River from the Kerrville vicinity to the delta (Table 2; figure 4). Two of these (New Braunfels and Bloomington) record stage only, and another (Tivoli) is at a flow control structure and withdrawal point and does not necessarily represent the discharge regime. The Victoria station is the downstream-most point with sufficient data to determine reliable long-term mean and median flows.

Table 2. Stream gaging stations in the study area. Code is the U.S. Geological Survey station identification code. Drainage area upstream of each station and the datum (above mean sea level NGVD29) of the gage are also shown. The distance is upstream of the river mouth.

| Name | Code | Area $km^2$ | Area $mi^2$ | Datum m | Datum ft | Distance km | Distance mi |
|---|---|---|---|---|---|---|---|
| Above Bear Cr. nr Kerrville | 08166140 | 1279 | 494 | 549 | 1800 | 624 | 388 |
| Kerrville | 08166200 | 1321 | 510 | 495 | 1623 | 620 | 385 |
| Comfort | 08167000 | 1350 | 521 | 488 | 1601 | 573 | 356 |
| Spring Branch | 08167500 | 2116 | 817 | 418 | 1371 | 530 | 329 |
| Sattler | 08167800 | 2311 | 892 | 289 | 948 | 493 | 306 |
| New Braunfels above Comal R. | 08168500 | 2443 | 943 | 226 | 742 | 459 | 285 |
| New Braunfels | 08169000 | 4279 | 1652 | 179 | 587 | 455 | 283 |
| Seguin | 08169792 | 5069 | 1957 | 178 | 584 | 399 | 248 |
| Gonzales | 08173900 | 5617 | 2168 | 123 | 404 | 282 | 175 |
| Cuero | 08175800 | 7941 | 3065 | 71 | 233 | 165 | 102 |
| Victoria | 08176500 | 13463 | 5197 | 29 | 95 | 68 | 42 |
| Bloomington | 08177520 | 15063 | 5814 | 0 | 0 | 40 | 25 |
| Tivoli | 08188800 | 26231 | 10125 | 0 | 0 | 11 | 7 |

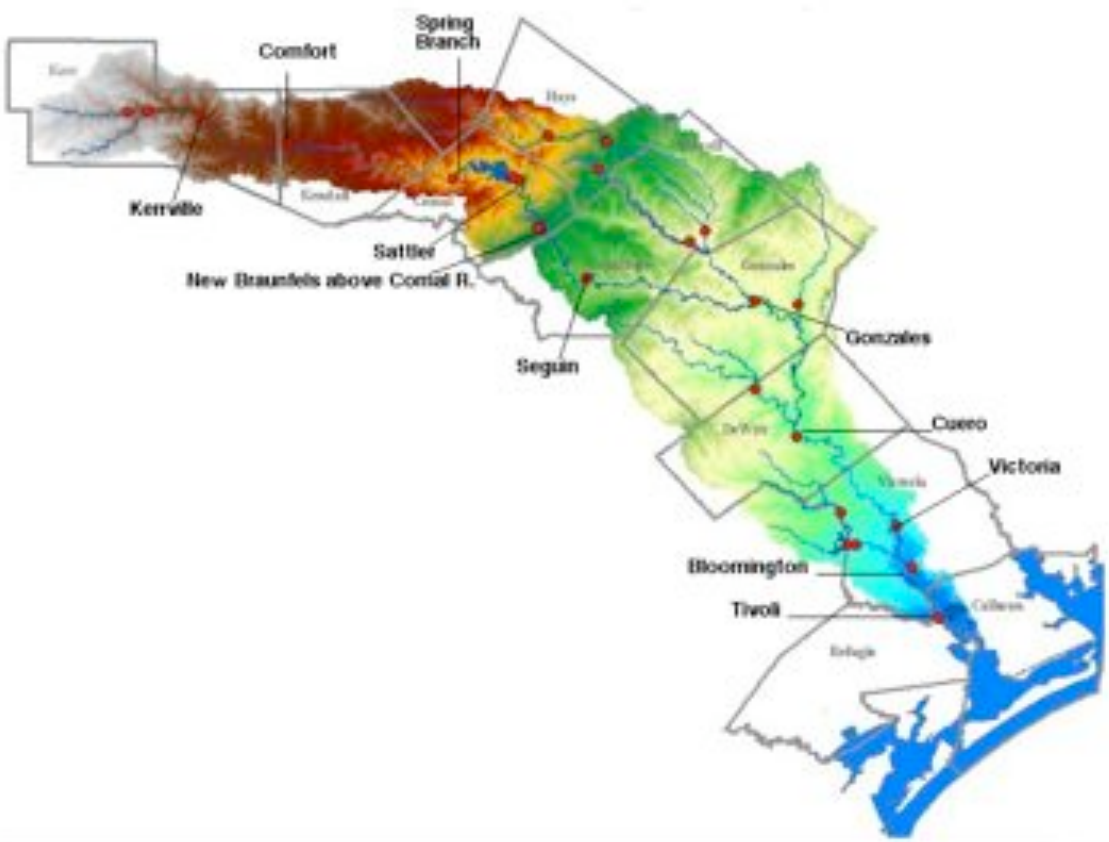


Figure 4. Location of gaging stations used in this study. Note that in some cases the gage sites are near but not in the towns they are named for (adapted from a GBRA map).

Mean, median, and flood-stage discharges are shown in Table 3. The flood discharge is based on the official flood-stage designations for each station by the National Weather Service's Advanced Hydrologic Prediction Service (http://water.weather.gov/ahps2/index.php?wfo=ewx). Mean discharges are typically strongly affected by very high discharge events. Therefore the median discharge, in this case reflecting the mean daily flow exceeded during 50 percent of the period of record, is a better indicator of typical or average flow conditions. These values are taken from Asquith and Heitmuller's (2008) flow duration curves. Table 3 shows the probability of flood flows and their relationship to median flows.

Table 3. Mean, flood stage, and median discharges for Guadalupe River gaging stations.

| Name | Code | Mean Q (cms) | Mean Q (cfs) | Flood Q (cms) | Flood Q (cfs) | Median Q (cms) | Median Q (cfs) |
|---|---|---|---|---|---|---|---|
| Above Bear Cr. nr Kerrville | 08166140 | 3.020 | 107 | | | 2.20 | 78 |
| Kerrville | 08166200 | 4.323 | 153 | 416.0 | 14691 | 2.82 | 100 |
| Comfort | 08167000 | 6.640 | 234 | 1132.8 | 40005 | 3.10 | 110 |
| Spring Branch | 08167500 | 10.822 | 382 | 1214.9 | 42905 | 5.07 | 180 |
| Sattler | 08167800 | *14.229* | 502 | *198.2* | 7001 | 5.92 | 210 |
| New Braunfels above Comal R. | 08168500 | *14.229* | 502 | *169.9* | 6001 | 6.20 | 220 |
| Seguin | 08169792 | 27.180 | 960 | 550.5 | 19441 | | |
| Gonzales | 08173900 | 59.620 | 2105 | 374.4 | 13220 | 28.45 | 1010 |
| Cuero | 08175800 | 61.875 | 2185 | 398.1 | 14060 | 28.73 | 1020 |
| Victoria | 08176500 | 56.721 | 2003 | 254.9 | 9001 | 28.17 | 1000 |
| Tivoli | 08188800 | 47.912 | 1692 | 0 | 0 | | |

Table 4. Exceedence probabilities (mean daily discharge) and ratios of flood to median discharge for Guadalupe River gaging stations.

| Station | Flood Q (cfs) | Flood Q (cms) | Probability | Flood Q/median Q |
|---|---|---|---|---|
| Kerrville | 14,691 | 416.0 | 0.08 | 146.91 |
| Comfort | 40,005 | 1132.8 | 0.01 | 363.68 |
| Spring Branch | 42,905 | 1214.9 | 0.06 | 238.36 |
| Sattler | 7,001 | 198.2 | 0.01 | 33.34 |
| New Braunfels (above Comal R.) | 6,001 | 169.9 | <0.01 | 27.28 |
| Gonzales | 13,220 | 374.4 | <0.01 | 13.09 |
| Cuero | 14,060 | 398.1 | <0.01 | 13.78 |
| Victoria | 9,001 | 254.9 | 0.04 | 9.00 |
| Bloomington[a] | 20 | 6.1 | 0.16 | |

[a]Stage-only station. Flood stages are given in feet and meters, respectively.

Median (and to a lesser extent mean) flows increase, as expected, in a downstream direction. The large increase between the station at New Braunfels upstream of the Comal River and the Gonzales station reflects the inputs of both the Comal and San Marcos Rivers, as well as other sources in the 1,225 $mi^2$ (3,174 $km^2$) of drainage area between the two stations. As discussed earlier, the Edwards Plateau portion of the Guadalupe River basin is subject to extreme flooding, which has resulted in very large channel capacities. Thus the Kerrville, Comfort and Spring Branch stations have relatively high flood probabilities (a one to eight percent chance mean daily flow will exceed the flood discharge), and very high ratios of flood to median discharge (Table 4). The Sattler station is in the gorge through the Balcones escarpment downstream of Canyon Lake, with a much smaller channel capacity and correspondingly lower flood/median ratio. These smaller channel capacities in the lower Guadalupe formerly caused severe flooding as large floods in the plateau region moved downstream, and this phenomenon was one major reason for construction of Canyon Lake.

Ratios of flood to median discharge decrease downstream of the escarpment, and the ratio is only 9.0 at Victoria. Flood probabilities are relatively low at the New Braunfels, Gonzales, and Cuero stations, due to the incised nature of the channels, and increases at Victoria and Bloomington in the lower coastal plain and delta (Table 4). Reduced flood discharges and more frequent overbank flow in the lower coastal plain has also been documented for the Sabine, Trinity, and Brazos Rivers (Phillips, 2007; 2008a; 2008b; Phillips and Slattery, 2007).

## FLOODS

In any river, floods account for a disproportionate amount of geomorphic change, beyond the obvious water resource management, engineering, and public safety concerns. As discussed in chapter 1, large floods have been particularly important in shaping both the geomorphology of the Guadalupe River valley and water resource management in the basin. Because of the spatial extent, climatic variability, and variations in hydrologic response, major floods on the river have distinctive synoptic characteristics with respect to their triggering events and effects on various portions of the river. This can be illustrated by briefly examining three significant floods that have occurred since 1998.

### *October 1998*

The Guadalupe River flood of 1998 is the flood of record for all gaging stations downstream of New Braunfels, and the third-highest flood ever recorded in New Braunfels. The recurrence interval for the recorded peaks was three to four times the estimated 100-year flood for the Gonzales, Cuero, and Victoria gaging stations, and was a 100-200 year event for the San Marcos and Blanco Rivers (Slade and Persky, 1999). This was not a major flood event upstream of New Braunfels in terms of records for gaging stations, but was sufficient to remove or reshape some rapids from the river upstream of Canyon Lake, resulting in reclassification from class II or III to class I or II in the scale used by kayakers and canoeists to rate difficulty. However, most of the excess flow in the upper basin was retained in Canyon Lake, and most of the flow in the lower river originated from runoff downstream of the lake.

According to the synthesis of Slade and Persky (1999), a combination of a low pressure trough over the western U.S., and two tropical cyclones in the eastern Pacific forced a very deep layer of moist air into Texas, while a high pressure ridge to the east confined the water vapor plumes to south-central Texas. This created a flow of moist air from the Gulf of Mexico toward the San Antonio area during the morning of October 17. Lifting due to upper-air divergent winds lifted the extremely moist air, forming heavy thunderstorms. The storms spread over the region, and by late morning the western Comal/eastern Medina County area had received about 15 in (380 mm) of rain. Before the day ended, several National Weather Service (NWS) 12-inch (300 mm) rain gauges had overflowed. In the Guadalupe River basin, areas from the Edwards Plateau to downstream of Cuero received at least 8 in (203 mm) of rain on October 17-18, 1998.

The timing of flood peaks at specific gaging stations allows an assessment of the rate of flood wave propagation downstream, as shown in Table 5. The gaging station at Seguin was not operational during this event.

Table 5. Flood wave velocity in the October, 1998 flood, based on timing of peaks at gaging stations.

| Stations | Distance/time difference (km $hr^{-1}$) | Mean Velocity (m $sec^{-1}$) |
|---|---|---|
| New Braunfels-Gonzales | 6.34 | 1.76 |
| Gonzales-Cuero | 4.29 | 1.19 |
| Cuero-Victoria | 7.19 | 2.00 |

*July 2002*

The flood of July, 2002 ranks as one of the top five flood stages for the stations at Spring Branch, Sattler, Gonzales, and Bloomington. Additionally, the July 2002 event produced a peak >5.5 ft (1.7 m) above flood stage at Kerrville, >9 ft (2.7 m) at Victoria, and at least 10 ft (3 m) above NWS-designated flood stages at every station in between. However, this event is most notable as the flood of record for Canyon Lake, and for the first time overtopping the spillway at Canyon Dam.

According to the NWS analysis of the event, a slow-moving tropical wave with an abundance of moisture moved west across the northern Gulf of Mexico and into south Texas during the week of June 30-July 7, 2002. The tropical wave moved inland over central Texas and became a stationary low-pressure system. Disturbances developed on the western side of the low over north central Texas and moved south through the middle of the state, generating intense precipitation. Later, disturbances developed on the eastern side of the low along the southern Mexican coast south of Brownsville, and moved north, spreading tropical rains into the Coastal Bend and Texas Hill Country. The low-pressure system remained stationary over south Texas for a week, bringing flooding to parts of the Texas Hill Country and south Texas. Total rainfall amounts of 25 to 35 inches (635 – 890 mm) were reported across the Texas Hill Country. This set the stage for July 14-16, when another heavy rainfall event occurred which caused the rivers to rise again. The Guadalupe, San Antonio, and other rivers all reached major flood levels. An area of 4,179 $mi^2$ (10,800 $km^2$) received at least 20 in (510 mm) of precipitation during the event (Earl and Dixon, 2005).

The most spectacular result of this flood event was the overtopping of the Canyon Dam spillway, with flow passing over the spillway for about six weeks. This carved the roughly 1 mile long Canyon Lake Gorge, a new channel up to 50 feet (15 m) deep, into the Glen Rose limestone.

*June 2010*

A major rainfall event beginning late June 8 and lasting into the afternoon of June 9 delivered seven to 12 inches (178 to 305 mm) of rain over an 18 hour period to portions of Atascosa, Bexar, Wilson, Comal, Guadalupe, and Lee Counties, according to National NWS measurements. This was not an extreme flood by the standards of the region, though it did result in the fourth-highest stage ever recorded at the Seguin gaging station, and considerable damage (figure 5). However, the event did allow a more detailed assessment of flood wave propagation than is possible for previous events.

Figure 5. Vehicles transported by the June, 2010 Guadalupe River flood, in Gruene (National Weather Service photo).

NWS reports indicated that abundant tropical moisture, coupled with a slow moving upper level low pressure system which moved northeast across the area, formed a large complex of showers and thunderstorms. The storms were very slow moving to near stationary, producing intense rainfall over the same area for several hours. The

Guadalupe River flooded in several areas, particularly around New Braunfels. Because the precipitation was concentrated in a specific part of the drainage basin, this event facilitates the tracking of a flood wave downstream.

The June 8-9 rain event did not cause any flooding upstream of Canyon Lake, and the Sattler gaging station in the gorge downstream of the dam did not flood, reaching a peak of only 474 cfs at 0700 on June 9. However, spring-fed streams near the base of the Balcones escarpment produced rapid responses. The Hueco Springs gage in the lower end of the Guadalupe River gorge upstream of New Braunfels failed due to flood damage late on June 8. The Comal River peaked at about 31,300 cfs and a stage of 28.64 feet at 0930 on June 9, according to USGS estimates. The San Marcos River near its spring source peaked at 250 cfs at 0845 on June 9, with the peak at the Luling gaging station (the downstream-most on the San Marcos) occurring in the early hours (0130) of June 10.

The Guadalupe River at New Braunfels upstream of the Comal River peaked at 52,400 cfs at 0900 on June 9, with a stage of 27.26 feet. The station downstream of the Comal peaked at 0930 at 29.65 ft. Thirty-five miles (57 km) downstream at Seguin, the peak (46,300 cfs; 33.09 ft) occurred at 1715 the same day. At the Gonzales gage, miles (118 km) downstream from Seguin, the Guadalupe peaked at 23,900 cfs and 37.74 ft at 0245 on June 11. The peak at Cuero, another 73 miles (117 km) downstream from Gonzales, occurred at 1200 on June 12, below flood stage at 13,500 cfs and 23.54 ft. Flood stage was reached at Victoria (71 mi/114 km downstream of Cuero), with the peak (13,400 cfs, 25.58 ft) reached June 13 at 0345. At a discharge of approximately 3000 cfs at the Victoria gaging station, flow in the delta area is not contained within the main Guadalupe River channel, some flowing instead through various distributary and high-flow channels, and spreading across the delta, including some flow into the Victoria barge canal (GBRA, personal communication). The USGS stage recorder at Bloomington apparently malfunctioned during the event. At Tivoli (42 mi/67 km downstream of Victoria), a peak stage of 7.70 ft was reached at 2200 on 6/13.

Flood wave propagation rates are shown in Table 6. Some flattening of the hydrograph is expected as a flood wave moves downstream, reducing the rate of propagation. Note, however, the higher velocity in the Cuero-Victoria reach (see also Table 5 above).

Table 6. Flood wave velocity in the June 2010 flood, based on timing of peaks at gaging stations.

| Stations | Time difference/ Distance (km $hr^{-1}$) | Mean Velocity (m $sec^{-1}$) |
|---|---|---|
| New Braunfels-Seguin | 7.23 | 2.00 |
| Seguin-Gonzales | 3.49 | 0.97 |
| Gonzalez-Cuero | 3.52 | 0.97 |
| Cuero-Victoria | 7.23 | 2.01 |
| Victoria-Tivoli | 3.67 | 1.02 |

STREAM POWER

Sediment transport capacity of flows is directly proportional to stream power. Cross sectional stream power (power per unit channel length, W $m^{-1}$) is a function of the product of slope (S) and discharge (Q),

$$\Omega = \gamma Q S \qquad (1)$$

where $\gamma$ is specific weight of water.

The slope term in the stream power equation is energy grade slope, or the change in hydraulic head per unit distance. In practice, the energy grade slope is typically approximated by water surface or channel bed slope. As shown by Phillips and Slattery (2007), water surface slopes may vary within, as well as between, specific flow events. Therefore a common practice is to use channel slopes in assessments of general longitudinal variations in stream power (as opposed to event-specific assessments, or sediment transport modeling; c.f. Knighton, 1999; Reinfelds et al., 2004; Jain et al., 2006).

Unless detailed field surveys are available, however, channel slope determinations are problematic, as slopes determined from topographic maps or digital elevation models are prone to considerable uncertainty. Beyond the potential errors inherent in any cartographic data extraction (whether manual or digital), topographic and DEM data are not detailed enough to include local slope variations such as riffles, pools, and knickpoints.

In some cases water surface elevations (stage plus gage datum) for a fixed time during a steady-state flow event can be used to determine water surface slopes between stations. However, many of the Guadalupe gaging stations are influenced by local impoundments or water barriers, making this method impractical. To get an idea of the general downstream pattern of stream power, the channel slope of the slope zone the station falls within (see chapter 3) was assigned to each station. Cross-sectional stream power was then determined for the median and flood flows (Table 7). Distances in Table 7 are based on measuring channel paths in the DEM.

Table 7. Relative cross-sectional stream power for median and bankfull (flood) discharges at Guadalupe River gaging stations.

| *Station* | *Distance Upstream of Tivoli (km)* | *Slope*[a] | *Median stream power ($W\ m^{-1}$)* | *Flood stream power ($W\ m^{-1}$)* |
|---|---|---|---|---|
| N Fork nr Hunt | 679 | 0.0012878 | 8.2 | 500.4 |
| Above Bear Cr. Nr Kerrville | 674 | 0.0012878 | 25.7 | |
| Kerrville | 670 | 0.0012878 | 32.9 | 5250.6 |
| Comfort | 627 | 0.0012878 | 36.2 | 14297.9 |
| Spring Branch | 518 | 0.0012878 | 59.3 | 15334.5 |
| Sattler | 482 | 0.0014180 | 76.2 | 2755.1 |
| NB above Comal | 448 | 0.0008606 | 48.4 | 1433.2 |
| New Braunfels | 444 | 0.0008606 | | 1672.1 |
| Seguin | 387 | 0.0008606 | | 4643.3 |
| Gonzales | 269 | 0.0002924 | 75.5 | 1072.8 |
| Cuero | 155 | 0.0002924 | 76.3 | 1141.0 |
| Victoria | 67 | 0.0003478 | 89.0 | 868.8 |

[a]Mean channel slope.

Cross sectional stream power for median flows (figure 6) shows a strong increase downstream through the Edwards Plateau and Balcones escarpment from <10 to about 75 $W\ m^{-1}$. $\Omega$ is reduced to <50 $W\ m^{-1}$ at New Braunfels due to reduced slope, but recovers to about 75 further downstream as flows from Comal and San Marcos Springs are added. Stream power peaks at the Victoria station at 89 $W\ m^{-1}$.

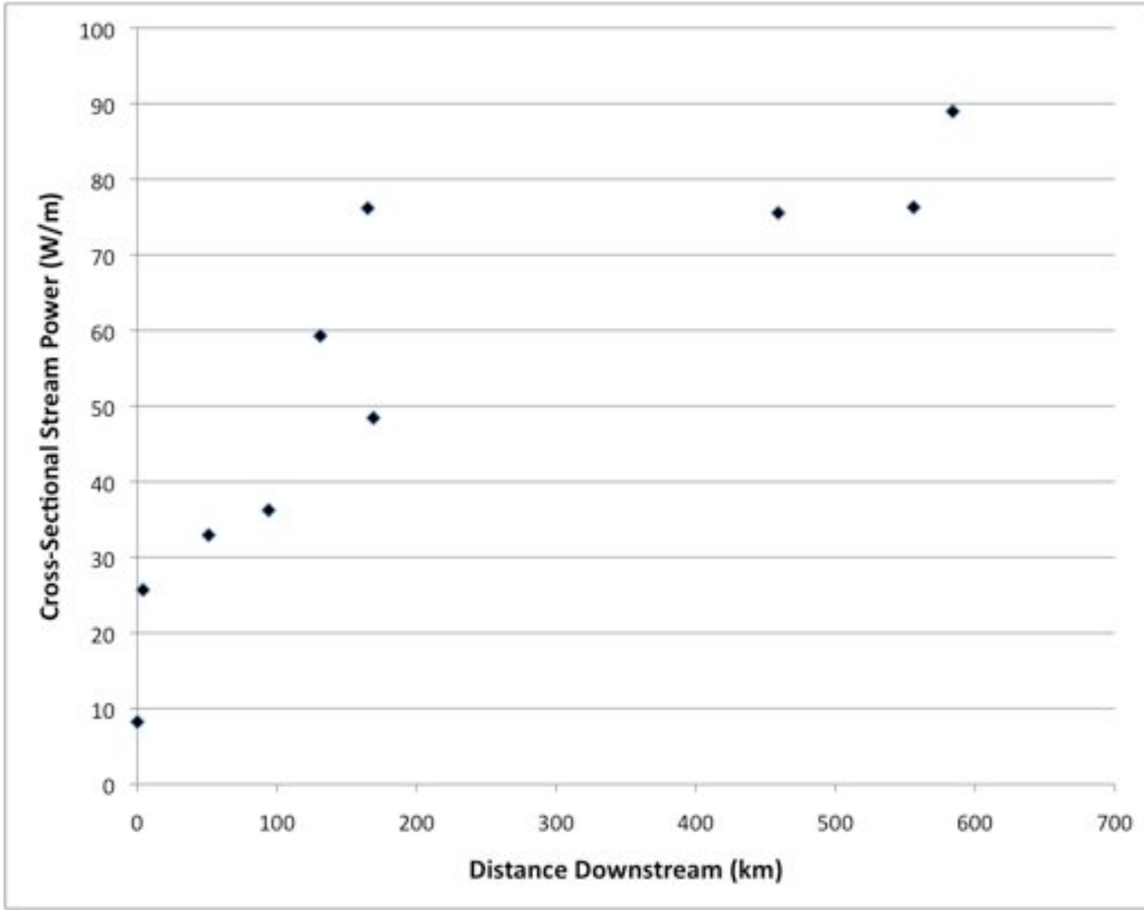


Figure 6. Cross sectional stream power associated with median daily flows at Guadalupe River gaging stations (see Table 7).

The pattern for flood flows (figure 7) is more complex. In the Edwards Plateau $\Omega$ increases rapidly with distance downstream, from about 500 to >15,000 W $m^{-1}$. At the Sattler station cross-section power is reduced due to flow regulation by Canyon Dam, and here and further downstream channel capacities are lower than at the Comfort and Spring Branch stations upstream of the lake. Flood power is >4,600 W $m^{-1}$ at the Seguin station, with the largest channel capacities downstream of the plateau, and decreases downstream to <1000 at Victoria.

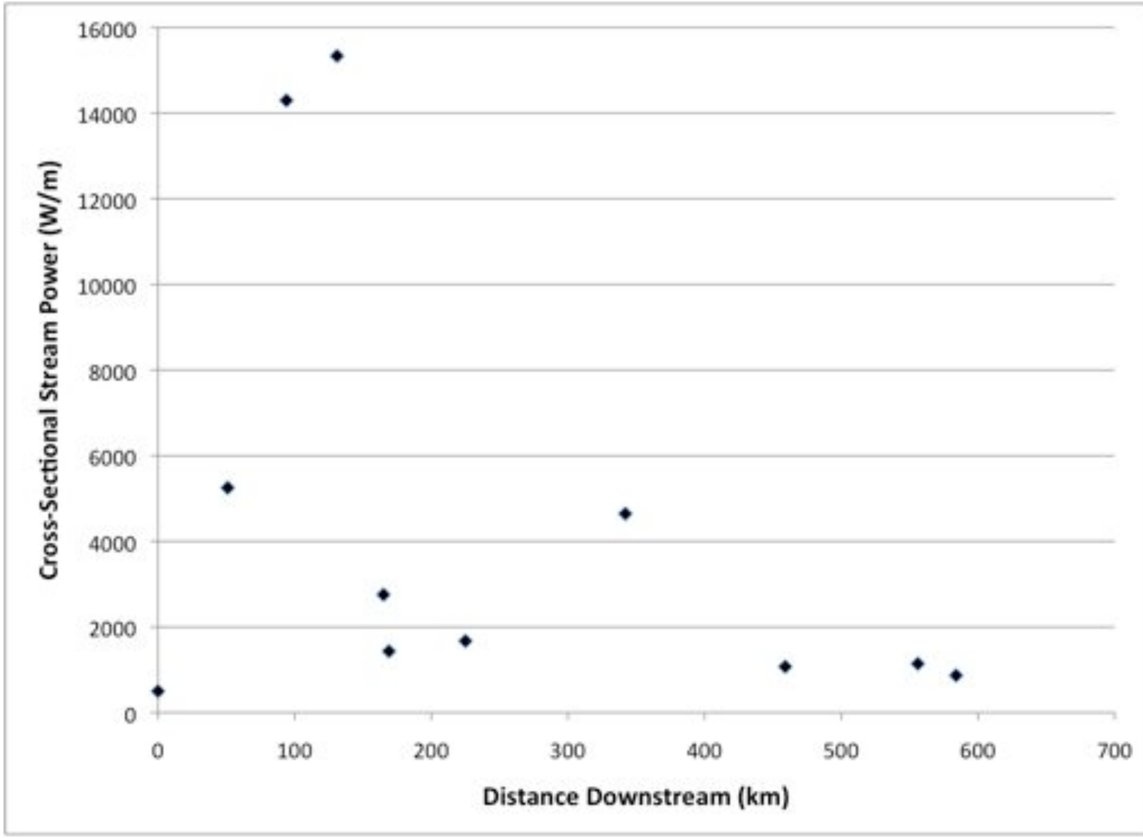

Figure 7. Cross sectional stream power associated with flood flows at Guadalupe River gaging stations (see Table 7).

In interpreting these data, recall that the stream power values are approximations using average reach-scale channel slopes. Also, note that bankfull (flood) flows at the stations vary greatly in their recurrence probabilities, from <0.01 at several stations to 0.04 to 0.08 at Victoria, Spring Branch, and Kerrville. The Spring Branch station represents a "hot spot" for geomorphic work, with the second-highest frequency of flood flow upstream of the delta, and the highest stream power for the flood discharge.

# Chapter 3
# Boundary Coincidence Analysis

BOUNDARY CRITERIA

*Slope*

Slope zones were identified from the DEM-derived channel network by examining the channel profile in detail and identifying significant breaks in slope over distances of approximately 5 km or more. Nine distinct slope zones were identified (Table 8), ranging from a negligible gradient through Canyon Lake, to 0.0014180 in the canyon just downstream of the lake. The lowest gradient other than the lake occurs in the lowermost 23 mi (37 km) of the river, and the steepest in the Edwards Plateau and Balcones escarpment area.

Table 8. Slope zonation. Relative slope is the channel gradient relative to that of the steepest reach. In this and subsequent tables, distance is upstream of the river mouth; latitude and longitude coordinates refer to the downstream end of the zone. Thus zone 3, for instance, begins 130 km (81 mi) upstream of the bay and ends 287 km (178 mi) upstream of the bay.

| *Zone* | *Distance km (mi)* | *Latitude* | *Longitude* | *Slope ($X 10^{-4}$)* | *Relative Slope* |
|---|---|---|---|---|---|
| 1 | 0 (0) | 28.458 | -96.818 | 0.455 | 0.032 |
| 2 | 37 (23) | 28.691 | -97.000 | 3.478 | 0.245 |
| 3 | 130 (81) | 29.058 | -97.222 | 2.924 | 0.206 |
| 4 | 287 (178) | 29.469 | -97.472 | 3.938 | 0.278 |
| 5 | 352 (219) | 29.514 | -97.734 | 8.173 | 0.576 |
| 6 | 380 (236) | 29.527 | -97.847 | 8.606 | 0.607 |
| 7 | 446 (277) | 29.710 | -98.106 | 14.18 | 1.000 |
| 8 | 484 (301) | 29.869 | -98.198 | <0.01 | <0.001 |
| 9 | 519 (322) | 29.860 | -98.388 | 12.878 | 0.908 |

*Sinuosity*

Sinuosity zones were determined using a combination of visual assessments of channel planform from aerial imagery and sinuosity measurements using RiverTools. Twelve sinuosity zones were identified (Table 9). Low sinuosity reaches (<1.5) are found in the lowermost 9 mi (15 km), and in a short reach on the Edwards Plateau. Otherwise, sinuosities range from about 1.8 to more than 2.9.

Table 9. Zonation based on sinuosity.

| *Zone* | *Distance km (mi)* | *Latitude* | *Longitude* | *Sinuosity* | *Sinuosity class* |
|---|---|---|---|---|---|
| 1 | 0 (0) | 28.458 | -96.818 | 1.280 | Low sinuosity |
| 2 | 15 (9) | 28.611 | -96.946 | 2.087 | Strongly meandering |
| 3 | 152 (94) | 29.067 | -97.333 | 1.779 | Meandering |
| 4 | 177 (110) | 29.194 | -97.311 | 2.643 | Strongly meandering |
| 5 | 205 (127) | 29.288 | -97.316 | 2.355 | Strongly meandering |
| 6 | 248 (154) | 29.448 | -97.401 | 2.927 | Strongly meandering |
| 7 | 376 (234) | 29.538 | -97.825 | 2.192 | Strongly meandering |
| 8 | 484 (301) | 29.869 | -98.198 | NA | Canyon Lake |
| 9 | 500 (311) | 29.862 | -98.382 | 2.207 | Strongly meandering |
| 10 | 518 (322) | 29.876 | -98.471 | 1.487 | Low sinuosity |
| 11 | 531 (330) | 29.885 | -98.531 | 2.042 | Strongly meandering |
| 12 | 542 (337) | 29.949 | -99.030 | 2.265 | Strongly meandering |

*Valley Width*

Valley width zones were delineated based on GIS measurements, reflecting both the mean width, and the variability in width associated with irregularities in valley wall geometry. Eleven zones were identified (Table 10). Valley width is greater in the coastal plain section of the river, and widest in the lowermost 48 mi (78 km) and minimum in the canyon downstream of Canyon Lake Dam. Five zones (2, 3, 5, 6, 11) all have mean valley widths between about 1.1 and 1.4 mi (1.76 - 2.26 km), but they are not all contiguous, and those that are vary considerably in the range of valley widths. The ratio of maximum and minimum widths within the zones ranges from 1.3 to nearly 6.5.

Table 10. Zonation based on valley width (VW).

| *Zone* | *Distance km (mi)* | *Latitude* | *Longitude* | VW mean km (mi) | VW range km | VW variability (max/min) |
|---|---|---|---|---|---|---|
| 1 | 0 (0) | 28.458 | -96.818 | 5.66 (3.52) | 4.5 – 7.0 | 1.56 |
| 2 | 78 (48) | 28.836 | -97.054 | 2.26 (1.40) | 1.0 – 2.8 | 2.80 |
| 3 | 142 (88) | 29.060 | -97.288 | 2.22 (1.38) | 0.8 – 4.3 | 5.37 |
| 4 | 224 (139) | 29.394 | -97.314 | 3.27 (2.03) | 1.1 – 7.1 | 6.45 |
| 5 | 337 (209) | 29.505 | -97.673 | 1.85 (1.15) | 0.9 – 3.5 | 3.89 |
| 6 | 401 (249) | 29.553 | -97.957 | 1.87 (1.16) | 1.4 - 2.1 | 1.50 |
| 7 | 452 (281) | 29.746 | -98.101 | 0.53 (0.33) | 0.3 – 0.8 | 2.67 |
| 8 | 484 (301) | 29.869 | -98.198 | Canyon Lake | NA | NA |
| 9 | 500 (311) | 29.862 | -98.382 | 1.47 (0.91) | 0.7 - 2.5 | 3.57 |
| 10 | 524 (325) | 29.867 | -98.422 | 0.70 (0.43) | 0.6 – 0.8 | 1.33 |
| 11 | 570 (354) | 29.905 | -98.638 | 1.76 (1.09) | 0.7 – 2.5 | 3.57 |

*Valley Confinement*

On the lower coastal plain and delta portion of the Guadalupe River is unconfined. The other eight zones delineated (Table 11) are all partly confined or confined. Other than the lower 48 mi (78 km), the river downstream of the Balcones Escarpment is mainly partly confined (zones 2, 4, 6), with relatively short (10 to 19 mi) confined reaches. The entire reach from the escarpment upstream is confined.

Table 11. Zonation based on valley confinement.

| *Zone* | *Distance km (mi)* | *Latitude* | *Longitude* | *Valley Confinement* |
|---|---|---|---|---|
| 1 | 0 (0) | 28.458 | -96.818 | Unconfined |
| 2 | 78 (48) | 28.836 | -97.054 | Partly confined |
| 3 | 111 (69) | 28.978 | -97.199 | Confined |
| 4 | 129 (80) | 29.043 | -97.235 | Partly confined |
| 5 | 327 (203) | 29.503 | -97.663 | Confined |
| 6 | 352 (219) | 29.515 | -97.736 | Partly Confined |
| 7 | 452 (281) | 29.746 | -98.101 | Confined |
| 8 | 484 (301) | 29.869 | -98.198 | Canyon Lake |
| 9 | 500 (311) | 29.862 | -98.382 | Confined |

*Geology*

The Guadalupe River valley can be subdivided into thirteen zones (Table 12) based on the geologic formations the valley is incised into, though at finer scales of resolution some of these could be further subdivided. This is particularly true of zones 5 and 6, characterized by narrow bands of various Miocene and Eocene formations, respectively. The lower 45 mi (72 km) of the river (zones 1-3) are Quaternary, grading to Pliocene and Miocene formations up to 142 mi (229 km) upstream. Bounding geology is Eocene up to 255 mi (411 km), while the remainder of the valley is bounded by Cretaceous Rocks. In some zones (6, 11) and the Quaternary zones, Pleistocene alluvial terraces that affect valley width and confinement are present.

Table 12. Geological zonation, based on formations bounding the valley walls.

| *Zone* | *Distance km (mi)* | *Latitude* | *Longitude* | *Geology* |
|---|---|---|---|---|
| 1 | 0 (0) | 28.458 | -96.818 | Beaumont Formation (Quaternary); Holocene delta |
| 2 | 8 (5) | 28.561 | -96.902 | Beaumont Formation, left bank; Lissie Formation; right bank; (Quaternary) |
| 3 | 72 (45) | 28.561 | -96.902 | Lissie (Quaternary) |
| 4 | 91 (57) | 28.883 | -97.188 | Willis & Goliad Formations (Pliocene) |
| 5 | 106 (66) | 28.972 | -97.174 | Narrow bands of Miocene formations (Fleming, Oakville, Catahoula) |
| 6 | 229 (142) | 29.408 | -97.325 | Narrow bands of various Eocene formations with inset Quaternary alluvial terraces |
| 7 | 339 (211) | 29.510 | -97.667 | Carrizo Sand & Recklaw Formation (Eocene) |
| 8 | 362 (225) | 29.532 | -97.769 | Wilcox Group (Eocene) |
| 9 | 411 (255) | 29.552 | -98.011 | Fredricksburg Group (Cretaceous) |
| 10 | 451 (280) | 29.743 | -98.108 | Glen Rose Formation and Fredricksburg Group (Cretaceous) |
| 11 | 465 (289) | 29.805 | -98.149 | Glen Rose Formation (Cretaceous) with inset Quaternary alluvial terraces |
| 12 | 524 (325) | 29.869 | -98.419 | Fredricksburg Group & Hensell Sand (Cretaceous) |
| 13 | 624 (388) | 29.965 | -98.888 | Fredricksburg Group (Cretaceous) |

*Channel-Floodplain Connectivity*

Table 13 shows channel-floodplain connectivity (CFC) zones, delineated on morphological criteria. This includes the extent and elevation (relative to the river bed) of floodplains, the typical bank heights or degree of incision, and the presence/absence and abundance of meander cutoffs, anabranches, paleochannels, sloughs, and floodplain depressions. Very high CFC indicates channel-floodplain fluxes at normal flow levels. High CFC suggests channel to floodplain flux at relatively frequent high but sub-bankfull flows. Moderate and low CFC zones suggest connectivity only during floods, and limited floodplain water storage with the moderate zones having generally lower and wider floodplains than the low category. Very low CFC indicates connectivity only during overbank floods, with water rapidly draining back to channel as flood peaks recede. These have higher banks and narrower (or no) floodplains than the low category. From the general vicinity of Seguin upstream—the plateau, escarpment, and uppermost coastal plain sections—CFC is low or very low, except for a 5.5 mi (9 km) moderate reach associated with backwater effects of Canyon Lake. Further downstream, CFC is moderate or high in the middle and lower coastal plain reaches, and very high in the delta.

These morphology-based assessments can be modified in some cases based on the frequency of overbank flows at gaging stations (Tables 2 and 3; chapter 2). The Kerrville station has a higher probability of daily mean flows exceeding the flood level than other stations in the Edwards Plateau area, suggesting a low rather than very low rating for zone 12. While flood stage at the Victoria gaging station is about 9,000 cfs, a flow at Victoria of about 3,000 results in overbank flows downstream in the delta. Exceedence probability of this mean daily discharge is about 9 percent. At the Bloomington station in the delta, probability of a mean daily stage exceeding flood stage is 16 percent. Based on this, the ratings for zones 3 and 2, respectively, can be raised to high and very high, effectively consolidating zones 1, 2 into a single very high CFC reach.

Table 13. Zonation by channel-floodplain connectivity based on valley morphology, modified by probability of overbank flows at gaging stations. The first term in the connectivity column indicates assessment based on morphological indicators alone. Where flood probabilities suggest a higher degree of connectivity, this is indicated in parentheses.

| *Zone* | *Distance km (mi)* | *Latitude* | *Longitude* | *Connectivity* | *Comments* |
|---|---|---|---|---|---|
| 1 | 0 (0) | 28.458 | -96.818 | Very high | delta |
| 2 | 18 (11) | 28.607 | -96.946 | High (Very high) | Numerous cutoffs, oxbows, sloughs, and paleochannels |
| 3 | 37 (23) | 28.691 | -97.000 | Moderate (High) | Low floodplain with few cutoffs, etc. |
| 4 | 135 (84) | 29.060 | -97.253 | High | Numerous cutoffs, oxbows, sloughs, and paleochannels |
| 5 | 350 (217) | 29.513 | -97.721 | Moderate | Low floodplain with few cutoffs, etc. |
| 6 | 415 (258) | 29.566 | -98.025 | Low | Incised; narrow valley; few cutoffs, etc.; influenced by lakes |
| 7 | 452 (281) | 29.746 | -98.101 | Very low | Canyon subject to releases from Canyon Lake |
| 8 | 484 (301) | 29.869 | -98.198 | Very low | Canyon Lake |
| 9 | 502 (312) | 29.901 | -98.323 | Moderate | Canyon Lake backwaters |
| 10 | 511 (317) | 29.888 | -98.368 | Very low | Incised; narrow valley with limited floodplain development |
| 11 | 594 (369) | 29.958 | -98.716 | Low | Relatively low & flat inside bends |
| 12 | 627 (389) | 29.959 | -98.897 | Very low (Low) | Narrow bedrock-controlled valley with limited floodplain development |

*Runoff and Streamflow*

The Guadalupe River exhibits distinct longitudinal variations in the major sources of runoff and streamflow, and effects on channel conveyance, due to a combination of natural hydrogeomorphic factors and human influences (figure 8). This results in eight zones as shown in Table 14.

Figure 8. Low-head dam near Center Point.

Table 14. Zonation based on sources of streamflow and flow regulation

| *Zone* | *Distance km (mi)* | *Latitude* | *Longitude* | *Description* | *Major streamflow sources & influences*[a] |
|---|---|---|---|---|---|
| 1 | 0 (0) | 28.458 | -96.818 | Delta below saltwater barrier and San Antonio River confluence | Tidal, spring flows, runoff, dam releases |
| 2 | 11 (7) | 28.506 | -96.884 | Delta above saltwater barrier and San Antonio River confluence | Spring flows, runoff, dam releases; tidal |
| 3 | 18 (11) | 28.607 | -96.946 | Coastal plain between San Marcos River & delta | Spring flows, runoff, dam releases |
| 4 | 287 (178) | 29.469 | -97.472 | Upper coastal plain between Comal & San Marcos Rivers | Dam releases, spring flows |
| 5 | 459 (285) | 29.715 | -98.110 | Canyon Dam to Comal River | Dam releases |
| 6 | 484 (301) | 29.869 | -98.198 | Canyon Lake | Lake & backwater effects; fluviokarst runoff |
| 7 | 511 (317) | 29.888 | -98.368 | Center Point to Canyon Lake backwaters | Fluviokarst runoff |
| 8 | 594 (369) | 29.958 | -98.716 | Upper Guadalupe River | Fluviokarst runoff; low-head dams |

[a]Listed in order of relative importance. "Runoff" refers to runoff and tributary inputs from non karst or fluviokarst sources originating below the Balcones escarpment.

The delta portion of the river is effectively divided into two zones in the vicinity of the GBRA saltwater control structure near Tivoli. The structure itself limits upstream effects of saltwater and tides, and is also a site for water diversions to industrial users and delta distributaries to the east. Further, the confluence of the San Antonio River/Elm Bayou occurs just upstream of the barrier, with a major freshwater input. The upstream limit of alluvial soils exhibiting saline properties, from U.S. Department of Agriculture Natural Resources and Conservation Service data (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm) was used as an indicator of chronic saltwater and tidal influence.

Zone 3, in the middle and lower coastal plain and uppermost delta, extends up to the confluence of the Guadalupe and San Marcos Rivers, and is thus influenced by dam releases, both major spring sources, and non-karst runoff and baseflow. Zone 4 lies between the two major springflow sources, the Comal and San Marcos Rivers. Zone 5, from Canyon Dam to the Comal, is overwhelmingly dominated by dam releases from Canyon Lake. The lake and its backwaters comprise zone 6. The Edwards Plateau area further upstream is characterized by fluviokarst hydrology. It is subdivided into two zones based on Kerrville Lake and a series of small low-head dams which occur down to the vicinity of Center Point.

## BOUNDARY COINCIDENCE

Locations where boundaries of two or more criteria above coincide are likely to be important "hinge points" or transitions in form-process relationships. Due to the fuzzy nature of some boundaries identified above (i.e., the change is a gradual transition rather than an abrupt demarcation), and the imprecision (or flexibility) in specifying some boundaries during the independent delineation of the zonations described above, two boundaries were considered to be coincident if they occurred within 5 km of a central point. The general location of these coincident boundaries is shown schematically in Figure 9. Figure 10 assigns a number to each of these points, and gives a brief description of the controlling factors. These are discussed further below.

Key transition point 1 is where the San Antonio River joins the Guadalupe in the delta region, very near the saltwater barrier at Tivoli. The river downstream is thus subject to greater saltwater influence than upstream, and also the greatly increased water and sediment inputs associated with the San Antonio River. Point 2 is controlled by the upstream limit of regular tidal and freshwater influence, as indicated by saline floodplain soils, and a local valley constriction by Quaternary terrace remnants. Coincident boundary point 3 is the uppermost delta, with greatly increased frequency of overbank flow, and the occurrence of distributary channels.

Point 4 is controlled by the transition from Pliocene to Pleistocene formations as the valley bounding units, and 5 by the Miocene to Pliocene transition. The latter, near Thomaston (between Cuero and Victoria), is also near where a past avulsion occurred. Coincident boundary 6 occurs at the confluence with a large tributary, Irish Creek. Geologic control is evident at point 7 (transition from Eocene to Miocene bounding formations), and 8 is at the San Marcos confluence, with a significant discharge increase. At point 9 valley widening occurs in connection with the outcropping of the relatively less resistant Carrizo Sand formation.

The coincident boundary at point 10 occurs within a mapped fault zone near Belmont, and is also characterized by a valley constriction associated with the Eocene Recklaw formation. At, and a short distance downstream from, this point several straight segments of the river channel occur, either normal to or aligned with the mapped fault trends (Figure 11).

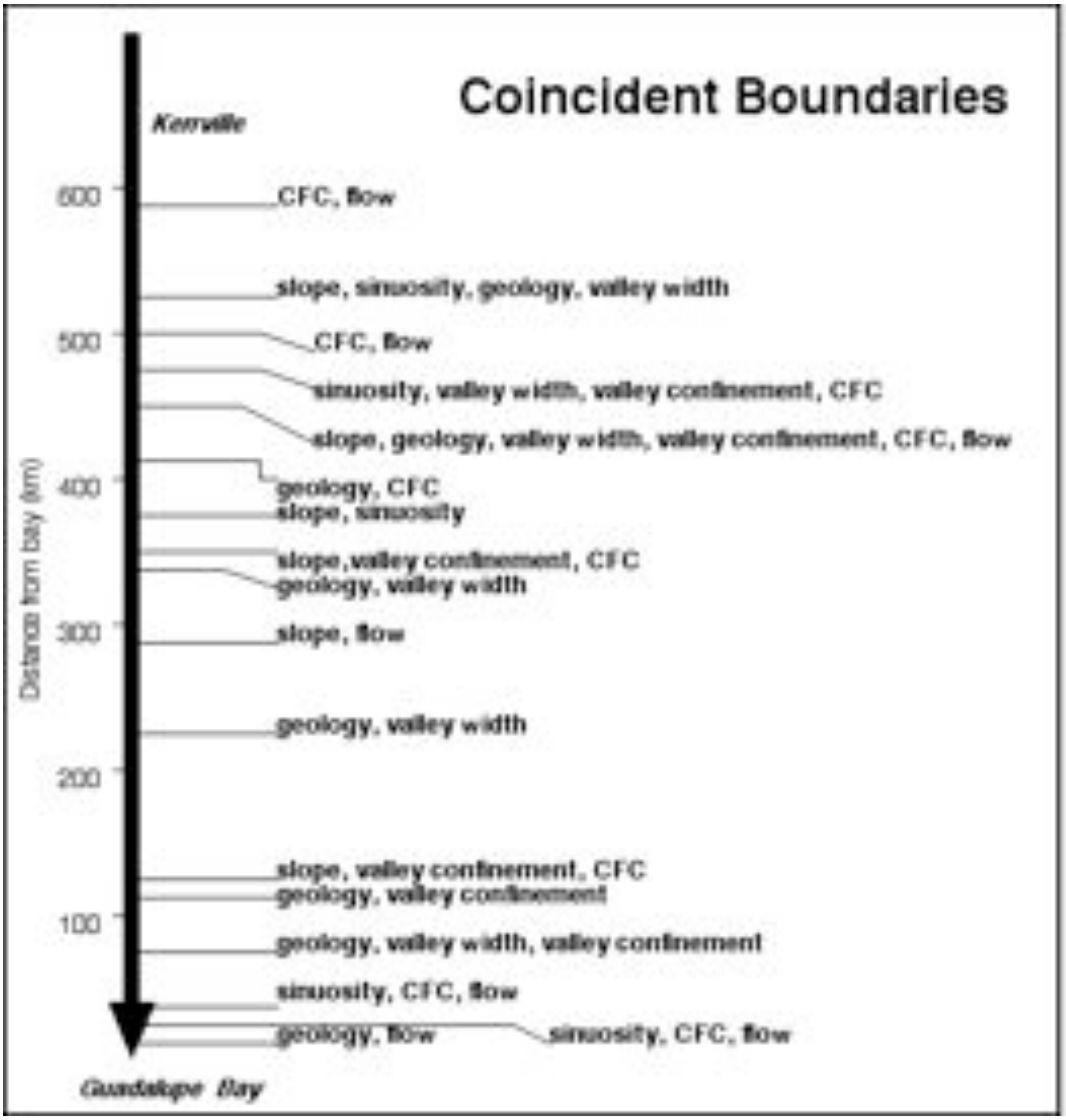


Figure 9. Schematic view of coincident boundaries along the Guadalupe River study area.

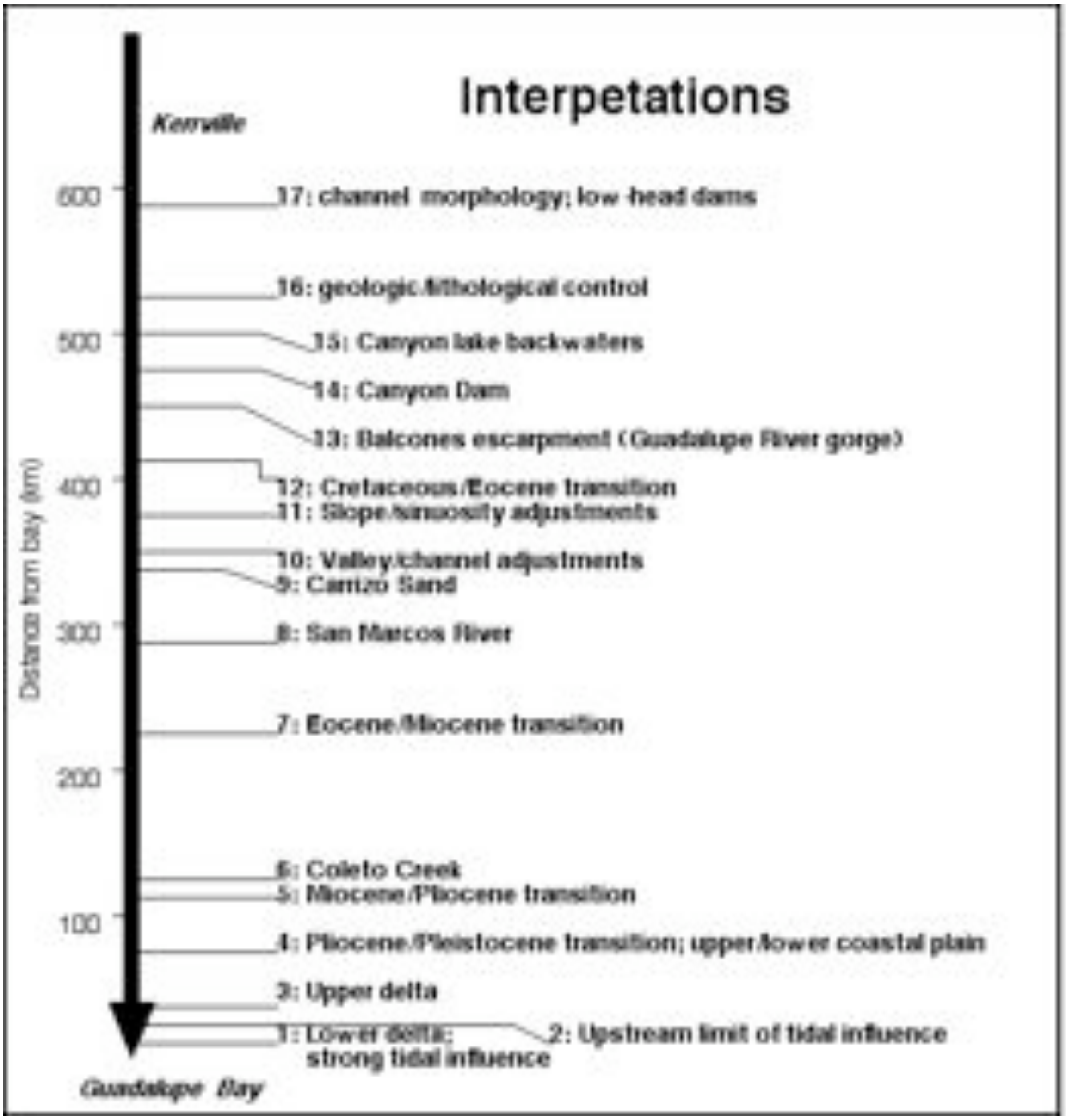


Figure 10. Interpretation of controlling factors relative to the coincident boundaries shown in figure 9.

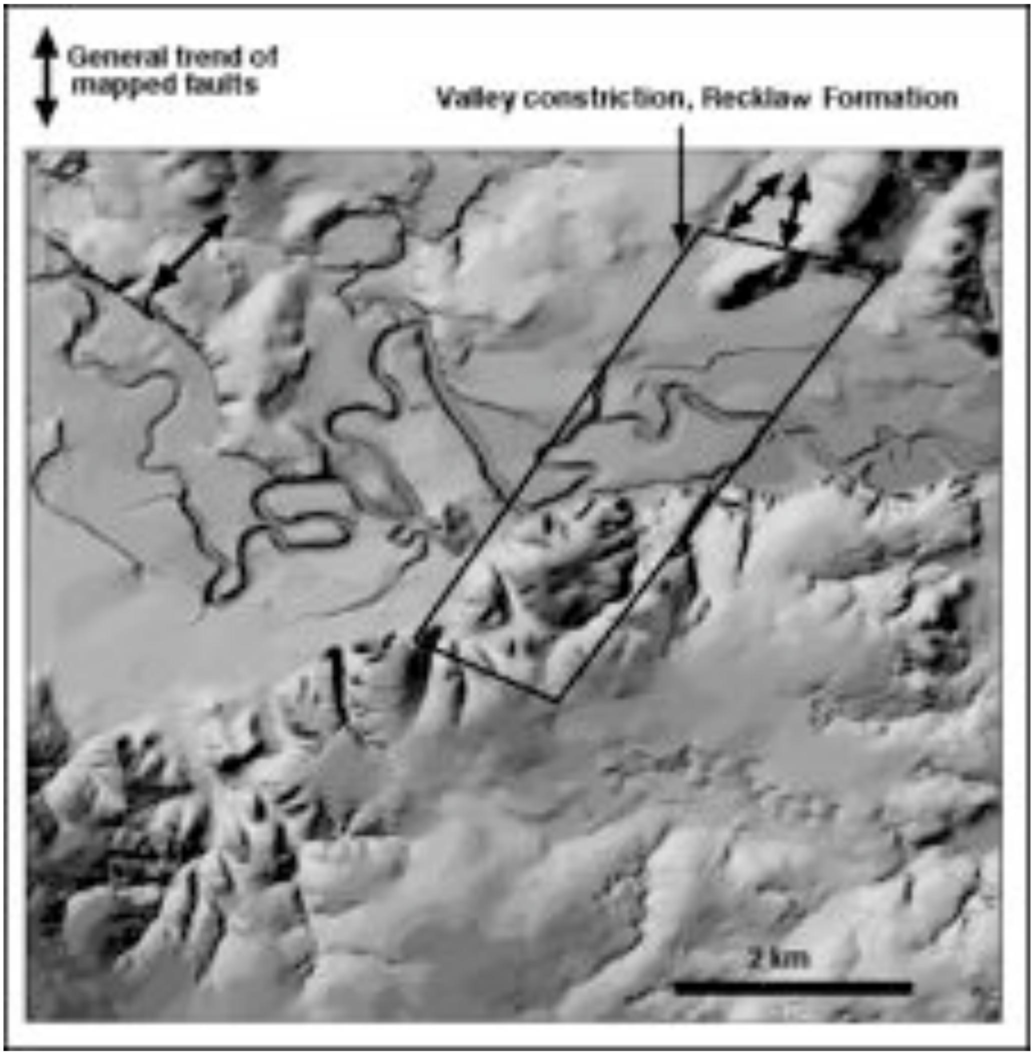


Figure 11. Shaded relief topography in the vicinity of coincident boundary 8 near Belmont. Note the straight channel segments.

Transition point 11 occurs where recent alluvium (downstream) rather than Quaternary terrace deposits are mapped in the valley bottom. This allows greater lateral migration and increased sinuosity, with a concomitant decrease in slope. Point 12 is collocated with the Cretaceous to Eocene transition in bounding geology, and 13 is the lower end of the Guadalupe River gorge, cut across the Balcones escarpment. Canyon Dam is the key control of point 14, but even in the absence of the structure this would be a key hinge point, as it occurs at the upstream edge of the escarpment and gorge, and also at a lithological boundary.

The location of point 15 is controlled by the backwater effects of Canyon Lake. Geology controls point 16. Stratigraphically, formations of the Fredericksburg Group overlie the Glen Rose Group, which overlies the Hensell sand. Upstream of 16 the Fredericksburg Group is the main valley bounding formation, but valley incision has exposed the Hensell sand (the Glen Rose is absent or negligibly thin here). Downstream, incision into the Fredericksburg has exposed the Glen Rose formations.

Coincident boundary 17 marks the downstream-most of a series of low-head dams on the upper Guadalupe, with the dams apparently located to take advantage of the narrow bedrock-controlled valley upstream. Field investigations also identified changes in channel form-process relationships in this vicinity. Upstream, channel beds are mostly bedrock, and exposed rock is relatively rough and pitted. Algal coatings are common, and rounded rock fragments rare (figure 12). Together these suggest limited abrasion, and channel erosion dominated by solutional processes (and perhaps cavitation during high flows). Downstream, alluvial covers on the bed are common (ranging from fine to boulders, depending on the local setting), rounded gravels are more common and algal coatings on exposed channel bedrock much less common, and the latter are smoother and less pitted. This indicates much greater relative importance of abrasion processes from here to Canyon Lake.


Figure 12. Guadalupe River channel near Kerrville, showing the rough, pitted surface and algal coatings.

Six of the coincident boundaries are associated with changes in the valley bounding formations. At five of these (points 4, 5, 7, 9, 16) the geological boundary is also associated with changes in valley width and/or confinement. At 16 changes in slope and sinuosity also occur. At point 12 the changes are expressed in terms of the degree of channel incision and associated changes in channel-floodplain connectivity. Two coincident boundaries are associated with the Balcones escarpment. One (14) at the top is the site of Canyon Dam, and the other (13) is where the gorge at the base of the escarpment terminates on the uppermost coastal plain. Each of these includes coincident boundaries of four or five of the boundary criteria. The distinctive topography of the gorge area is evident in Figure13.

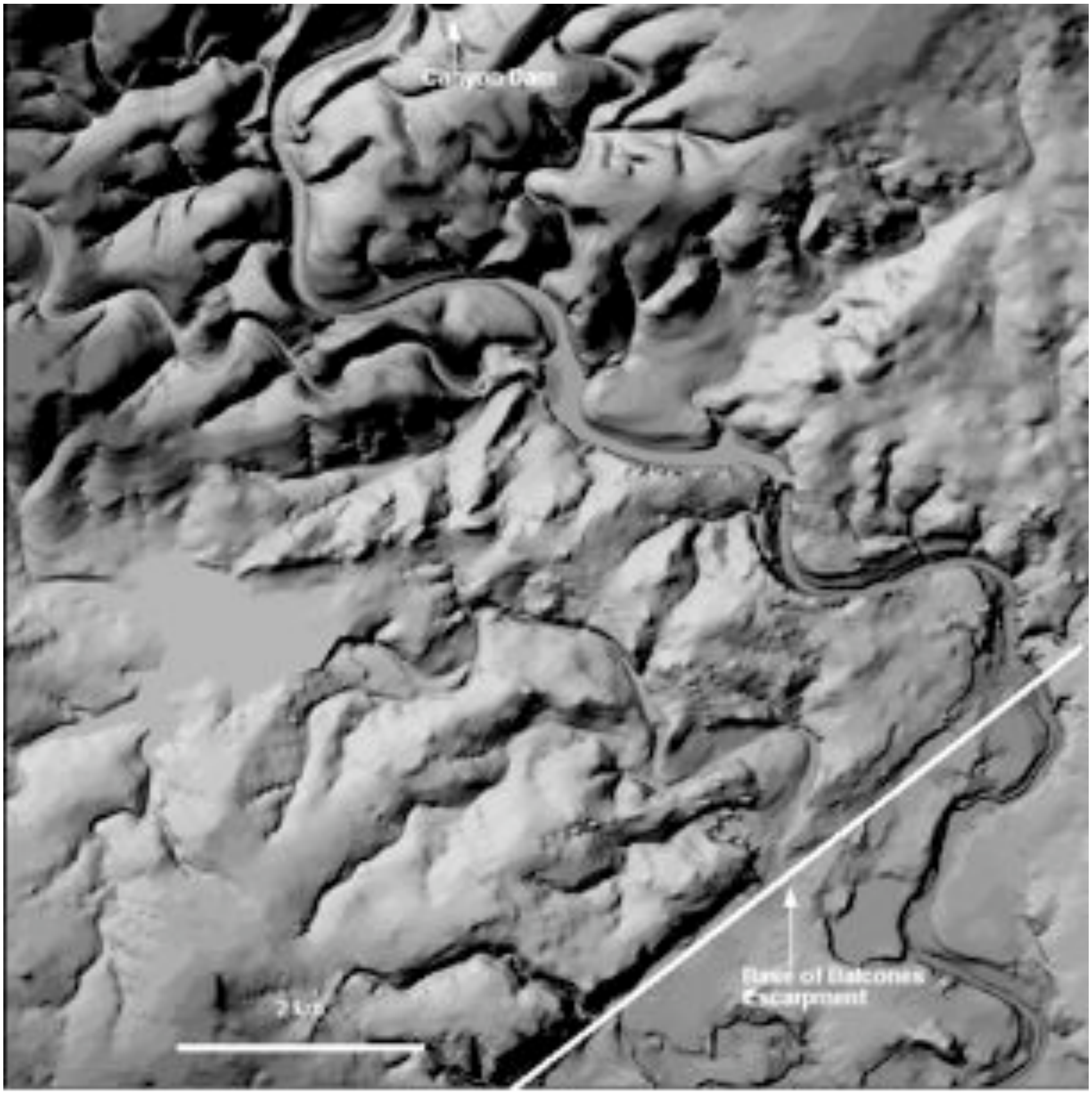


Figure 13. Topography (shaded relief) of a portion of the Guadalupe River gorge between Canyon Dam and New Braunfels.

Two coincident boundaries (points 6, 8) are associated with major tributary junctions. The San Marcos River (8) is a major water input; the change in slope (decrease downstream) is presumably related to the higher stream power associated with the increased flow. The Irish Creek junction (6) actually shows an increase in slope downstream, along with a transition from partly confined to a confined valley, and a decrease in CFC due to fewer cutoffs, etc. The latter is likely related to reduced lateral channel change in the confined valley downstream of point 6.

Transition points 1-3 are all in the delta downstream of Victoria. Differences between them are associated with tidal and saltwater influence, the San Antonio River confluence, channel-floodplain connectivity, and sinuosity. The latter two are associated with avulsive channel shifts in the delta, which are common and expected in deltaic environments. At least one geologically recent avulsion site is evident near Victoria, and at least two more within the modern delta. Point 3, at the confluence of Coleto Creek, is also influenced by a tectonic subsidence feature, the post-Vicksburg flexture (Ouchi, 1985). Donaldson et al. (1970) attribute morphological changes here and at a comparable point on the lower San Antonio River to the alluvial valley-to-delta transition, while Ouchi (1985) favors tectonic effects. The sinuosity change, in particular, is consistent with theoretical and experimental evidence of subsidence influences (Ouchi, 1985; Schumm et al., 2000). A combination of the two explanations is most likely—the flexure controls the location of the delta apex. Antecedent morphological features often cause the upstream translation of effects of Holocene sea level rise to stall until accretion allows the flooding surface to "climb" the feature, as has been shown in other Texas Rivers (Rodgriguez et al., 2005; Phillips and Slattery, 2008).

*Potential Future Changes*

Transition points 1-3 are the most likely foci of future change. Holocene and contemporary sea level rise will result in the gradual inundation or landward translation of the Guadalupe Bay/San Antonio Bay estuary, the Guadalupe and San Antonio River deltas, and associated wetlands, including riverine wetlands of the delta and lower coastal plain. The gradually rising base level may induce increases in sinuosity and lateral migration upstream of point 3 as well. In addition, deltaic environments are normally subject to channel avulsions, and the Guadalupe River is no exception, as noted above. Further, the lower San Antonio River has undergone several historic avulsions, and is currently undergoing a shift to the Elm Bayou channel near Tivoli.

Any future changes in transition points 14 and 15 will depend on the operation and maintenance of Canyon Lake and Dam. Given the propensity for large floods in the Edwards Plateau/Balcones Escarpment region, local morphological changes are likely in the vicinity of transition points 14-17. These are likely to be in the form of local scour or fill; channel widening or narrowing; removal, creation, modification or transportation of rapids and knickpoints; and bedform migration, with little or no spatial displacement of the transition points.

# Chapter 4
# Geomorphic Zones and River Styles

## INTRODUCTION

This chapter synthesizes the information in chapters 2 and 3 to develop a geomorphic zonation of the Guadalupe River. These zones are river styles, in the sense of Brierley and Fryirs (2005), conceptually similar to those developed for the lower Brazos and Navasota Rivers (Phillips, 2006; 2007a) and the lower and middle Trinity River, Texas (Phillips, 2008b; 2010).

The first phase in applying river styles within a given catchment is the identification of landscape units, which are broad-scale geomorphological divisions based on lithology, topography, and physiography. The Guadalupe River landscape units are shown in Figure 14. These include the Edwards Plateau, from the headwaters to the Balcones escarpment, the escarpment itself, the upper, middle, and lower coastal plains, and the delta.

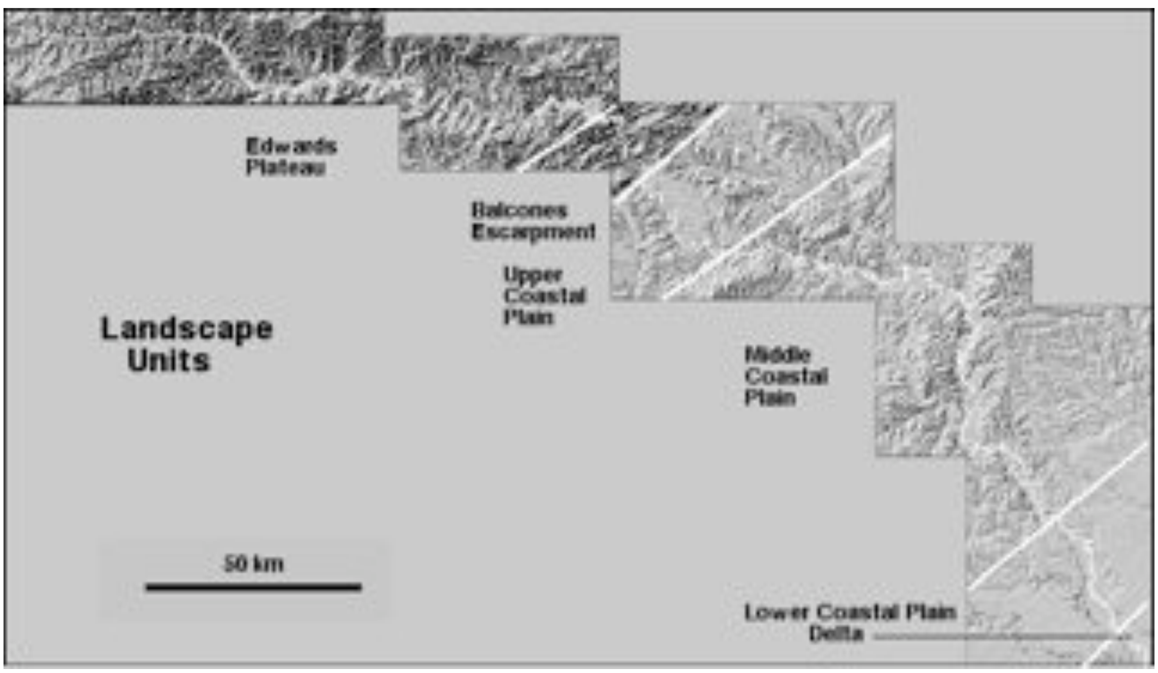


Figure 14. Guadalupe River valley landscape units.

## GEOMORPHIC ZONES

Within the six landscape units, 13 geomorphic zones or river styles were identified. These are listed in Table 15 and shown in Figure 15.

Table 15. Geomorphic zones (river styles) of the Guadalupe River. The locational coordinates shown are for the downstream end of the reach, which corresponds with the upstream end of the following reach (e.g., the downstream end of zone 3 is the upstream end of zone 2, etc.). Approximate distance upstream of Guadalupe Bay, and a general locational description relative to map landmarks is given. (US, DS = upstream, downstream; TX = Texas state highway; U.S. = U.S. highway)

| *Zone* | *Distance[a] km (mi)* | *Length km (mi)* | *Latitude* | *Longitude* | *Nearby landmark* |
|---|---|---|---|---|---|
| 1-Lower Delta | 0 (0) | 11 (7) | 25.548 | -96.818 | River mouth at Guadalupe Bay |
| 2-Middle Delta | 11(7) | 7 (4) | 28.506 | -96.884 | Saltwater barrier near Tivoli |
| 3-Upper Delta | 40 (25) | 29 (18) | 28.608 | -96.946 | RR crossing near Bloomington |
| 4-Lower Coastal Plain | 78 (48) | 38 (24) | 28.698 | -97.013 | Coleto Creek confluence |
| 5-Coastal Plain Transitional | 130 (81) | 52 (32) | 28.836 | -97.054 | US 77 crossing, Victoria |
| 6-Middle Coastal Plain | 287 (178) | 157 (98) | 29.058 | -97.222 | Downstream of Cuero |
| 7-Upper Coastal Plain | 327 (203) | 40 (25) | 29.469 | -97.472 | San Marcos River confluence near Gonzales |
| 8-Belmont Fault Zone | 362 (225) | 35 (22) | 29.503 | -97.663 | Hwy 80 crossing |
| 9-Escarpment-Plain Transition | 380 (236) | 79 (49) | 29.527 | -97.847 | Downstream of FM 1117 crossing |
| 10-Guadalupe River gorge | 459 (285) | 25 (16) | 29.715 | -98.110 | New Braunfels |
| 11-Canyon Lake | 484 (301) | 27 (17) | 29.869 | -98.198 | Canyon Dam |
| 12-Lower Plateau | 511 (317) | 83 (52) | 29.888 | -98.368 | Rebecca Creek Road |
| 13-Upper Plateau | 594 (369) | 126 (78) | 29.958 | -98.716 | Sisterdale Rd. crossing downstream of Comfort |

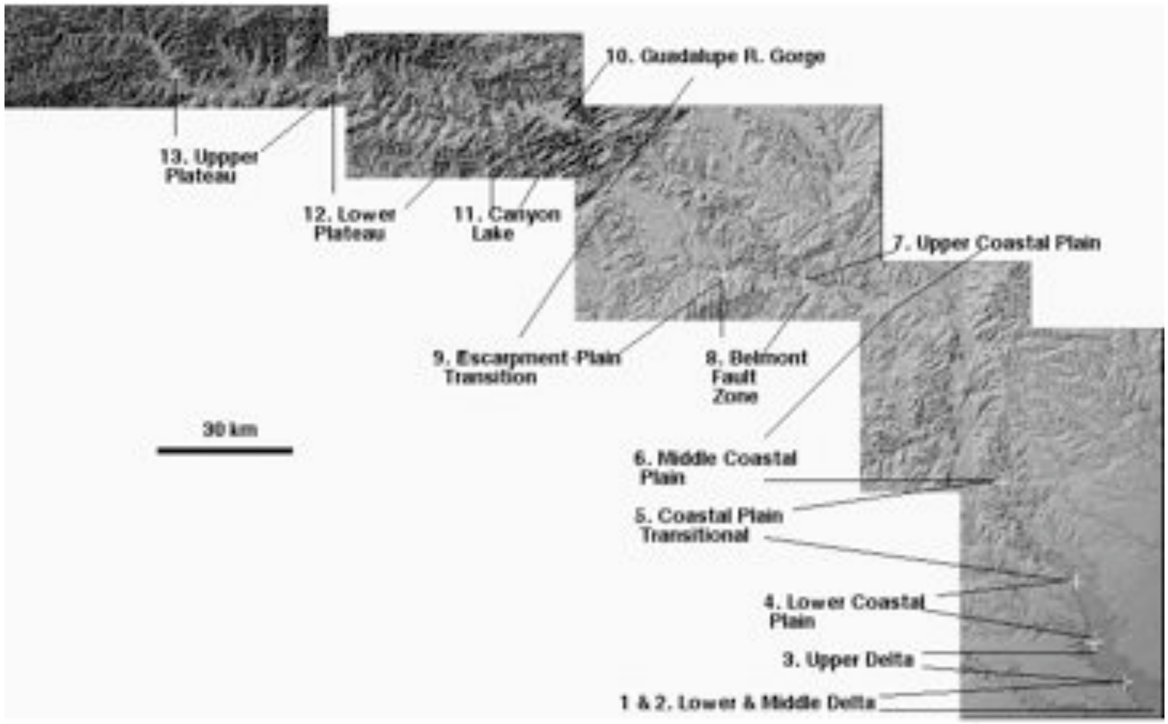

Figure 15. Geomorphic zones (river styles) of the Guadalupe River.

ZONE DESCRIPTIONS

General characteristics of each zone according to the boundary criteria are shown in Table 16, with brief descriptions of each zone following.

*1. Lower Delta*

This zone is the lowermost 6.5 mi (11 km) of the river from the San Antonio River confluence near the saltwater barrier at Tivoli to Guadalupe Bay. Situated entirely within the Holocene Guadalupe/San Antonio River deltas, this river style is characterized by very low slope, low sinuosity, a wide unconfined valley, and very high channel-floodplain connectivity. The latter is related to frequent flooding, low channel banks (Fig. 16), and numerous active, semi-active, and abandoned distributary channels. The lower delta is influenced by tides, saltwater, and water diversions by the Guadalupe-Blanco River authority.

Table 16. Characteristics of the geomorphic zones (river styles).

| *Zone* | *Slope* | *Sinuosity* | *Valley*[a] | *Geology* | *Flow and connectivity*[b] |
|---|---|---|---|---|---|
| 1-Lower Delta | 0.0001285 | 1.70 | Wide (7 km); UC | Holocene delta | Very high CFC; tidal & saltwater influences, San Antonio River confluence |
| 2- Middle Delta | 0.0001909 | 1.53 | Wide (6-7 km); UC | Holocene delta; Quaternary Beaumont | Very high CFC; tidal & saltwater influences (less than zone 1) |
| 3-Upper delta | 0.0000598 | 1.85 | Wide (5-6 km), UC | Holocene delta; Quaternary Beaumont | Very high CFC; flow derived from runoff, dam releases & springs |
| 4-Lower Coastal Plain | 0.0003264 | 2.38 | Wide (4.5-5.5 km), UC | Quaternary Lissie & Beaumont | High CFC; flow derived from runoff, dam releases & springs |
| 5-Coastal Plain Transitional | 0.0003732 | 1.78 | Moderate (1-2.8 km); C & PC | Miocene, Pliocene | High CFC; flow derived from runoff, dam releases & springs |
| 6-Middle Coastal Plain | 0.0002719 | 2.99 | Moderate to wide; variable (0.8-7.1 km); PC | Eocene | Moderate CFC; flow derived from runoff, dam releases & springs; strong influence of San Marcos River |
| 7-Upper Coastal Plain | 0.0006118 | 2.39 | Moderate (0.9 to 3.5 km); PC | Eocene; Carrizo Sand | Moderate CFC; flow dominated by dam releases & Comal River |
| 8-Belmont Fault Zone | 0.0006500 | 2.66 | Moderate (1.4 to 2.1 km); C & PC | Eocene; Carrizo Sand & Recklaw fmns | Moderate CFC; flow dominated by dam releases & Comal River |
| *Continued on following page* | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| 9-Escarpment to Plain Transition | 0.0010145 | 2.03 | Moderate (1.4 to 2.1 km); PC | Cretaceous & Eocene | Low to very low CFC; flow dominated by Comal River, other springs, and dam releases |
| 10-Guadalupe River Gorge | 0.0016922 | 2.01 | Narrow (0.3-0.8 km); C | Cretaceous | Very low CFC; flow dominated by dam releases |
| 11-Canyon Lake | Negligible (<0.000001) | Impounded | Flooded valley | Cretaceous | Impounded lake |
| 12-Lower Plateau | 0.0010872 | 2.35 | Moderate to narrow (0.6 to 2.5 km); C | Cretaceous | Fluviokarst runoff |
| 13-Upper Plateau | 0.0014378 | 1.66 | Narrow (<1 km); C | Cretaceous | Fluviokarst runoff |

[a]C, PC, UC = confined, partly confined, unconfined, respectively.
[b]CFC = channel-floodplain connectivity.

*2. Middle Delta*

A short reach from the railroad crossing near Bloomington to zone 1, this river style is similar to the lower delta. However, it is upstream of the San Antonio River inputs. There is evidence of regular saltwater and tidal influences here, but less than in zone 1 due to the saltwater barrier near Tivoli. This river style exhibits low slope and is strongly meandering at the upper end but transitions to low sinuosity. The valley is wide and unconfined. The geological setting is dominated by Holocene deltaic deposits, but Quaternary (Beaumont formation) valley walls do influence its morphology. Several avulsions have created both distributary channels and paleochannels. This and the low banks lead to high connectivity.

Figure 16. Low banks typical of the Guadalupe River and distributaries in the lower and middle delta.

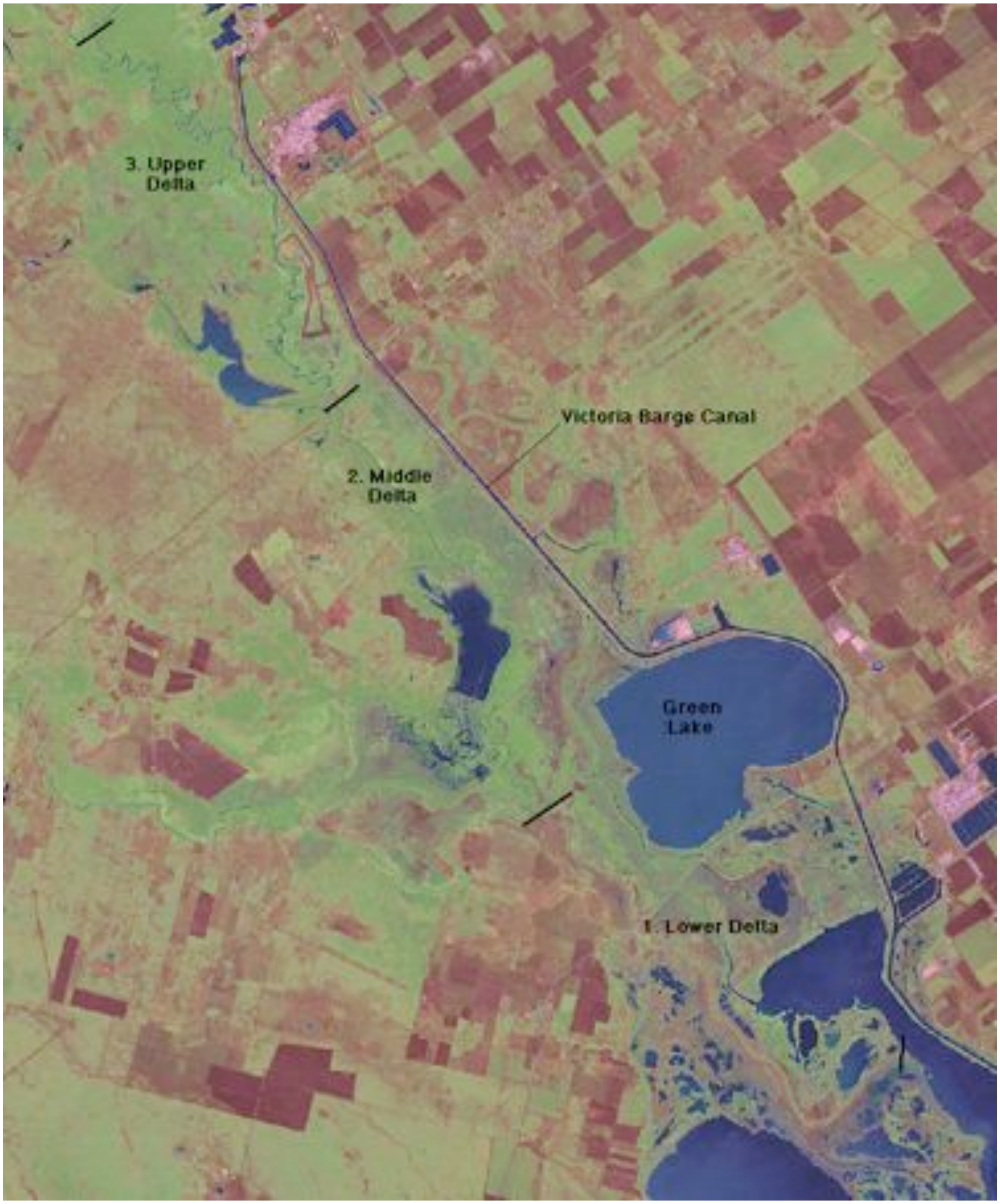

Figure 17.  Zones 1, 2, 3, shown on a LANDSAT satellite image. Zone boundaries are indicated with black bars.

*3. Upper Delta*

The upper delta extends from Coleto Creek to zone 2. Characteristics are generally the same as for the middle delta, with the exception of the absence of regular saltwater or coastal backwater effects. The Victoria Barge Canal begins upstream of this zone and passes through zones 1-3 parallel to the river. The canal does not convey significant flow during most flow conditions (> 3000 cfs at Victoria), but does receive some distributary flow at higher discharges.

*4. Lower Coastal Plain*

The lower coastal plain river style extends from approximately the Pliocene/Pleistocene boundary just upstream of Victoria to Coleto Creek. The reach is strongly meandering, with low slope and a wide, unconfined valley. There are few cutoffs, sloughs, etc., but the floodplain is relatively low and wide, and overbank flow relatively common, creating high CFC. Discharge here is significantly influenced by dam releases, springflow, and non-karst runoff.

Figure 18. Typical sandy point-bar and cutbank on the Guadalupe River in zone 4.

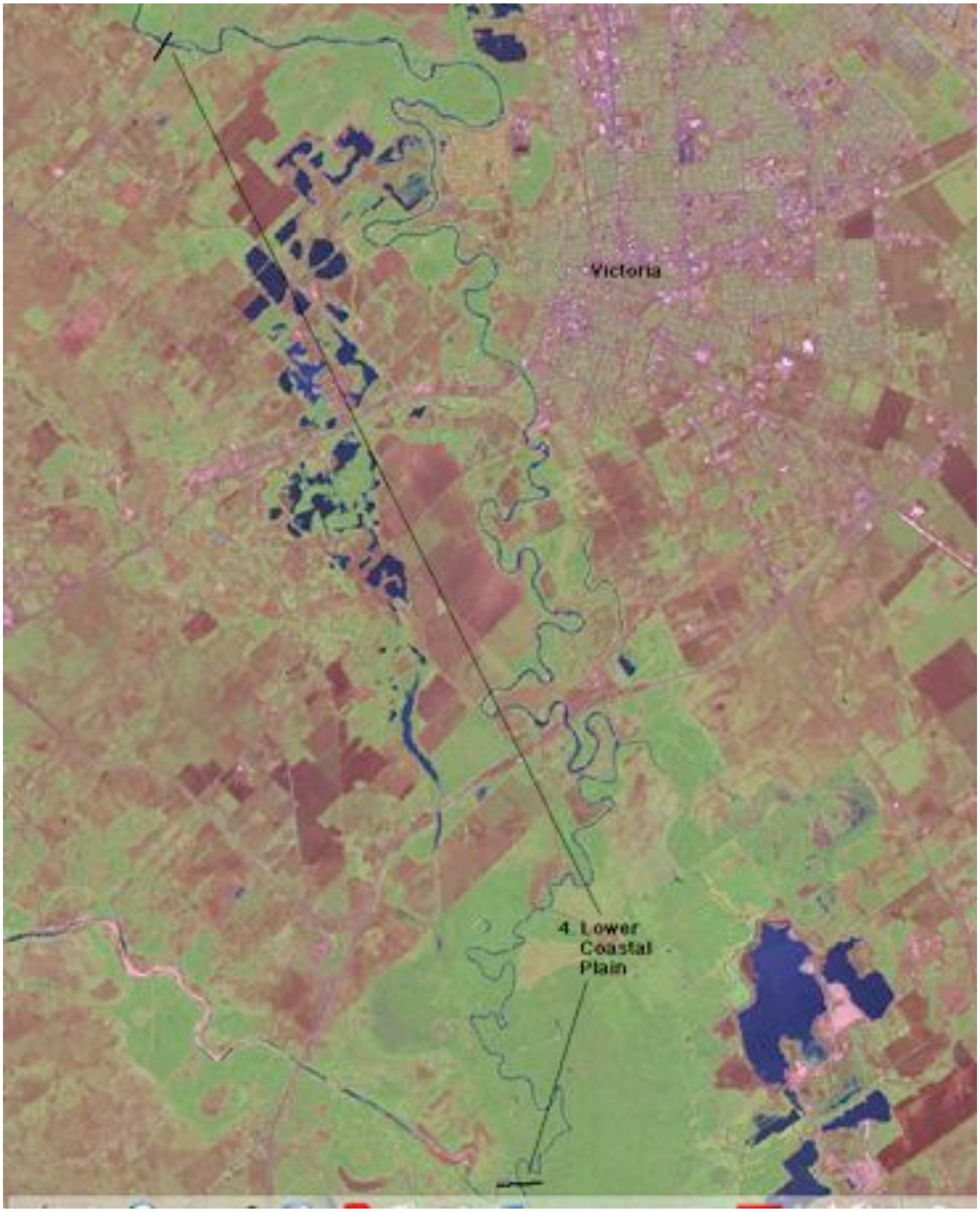


Figure 19. Zone 4 shown on a LANDSAT satellite image. Zone boundaries are indicated with black bars.

*5. Coastal Plain Transitional*

This river style is so named because the upper part of the reach includes a transition from Miocene to Pliocene valley walls, from a confined to partly confined valley, and an increase in sinuosity. The key distinguishing characteristics are a lower slope and stream power than the up- or downstream zones. The valley width is also more consistent than upstream (zone 6), where mean valley width is similar but the variability much greater.

*6. Middle Coastal Plain*

The upstream end of this reach, at the San Marcos River confluence, marks the point at which all karst and fluviokarst inputs in the Guadalupe River basin are reflected in the river discharge. Channel slope of zones 6 and 7 is less than any upstream reach other than Canyon Lake, and higher than any downstream reach. The slope transition is nearly twofold compared to zone 7 upstream. Sinuosity is variable, but mostly >2, with the exception of one meandering subreach (sinuosity = 1.8). This river style is partly confined, but includes several valley width zones, with mean widths of 1.85 to 3.27 km, and maximum/minimum width ratios of 3.9 to 6.4 within the latter. Geology of the bounding formations is Eocene, with the Carrizo Sand among these associated with wider valleys. Channel-floodplain connectivity is high, due largely to numerous paleochannels and depressions associated with lateral channel changes, a key feature of this zone.

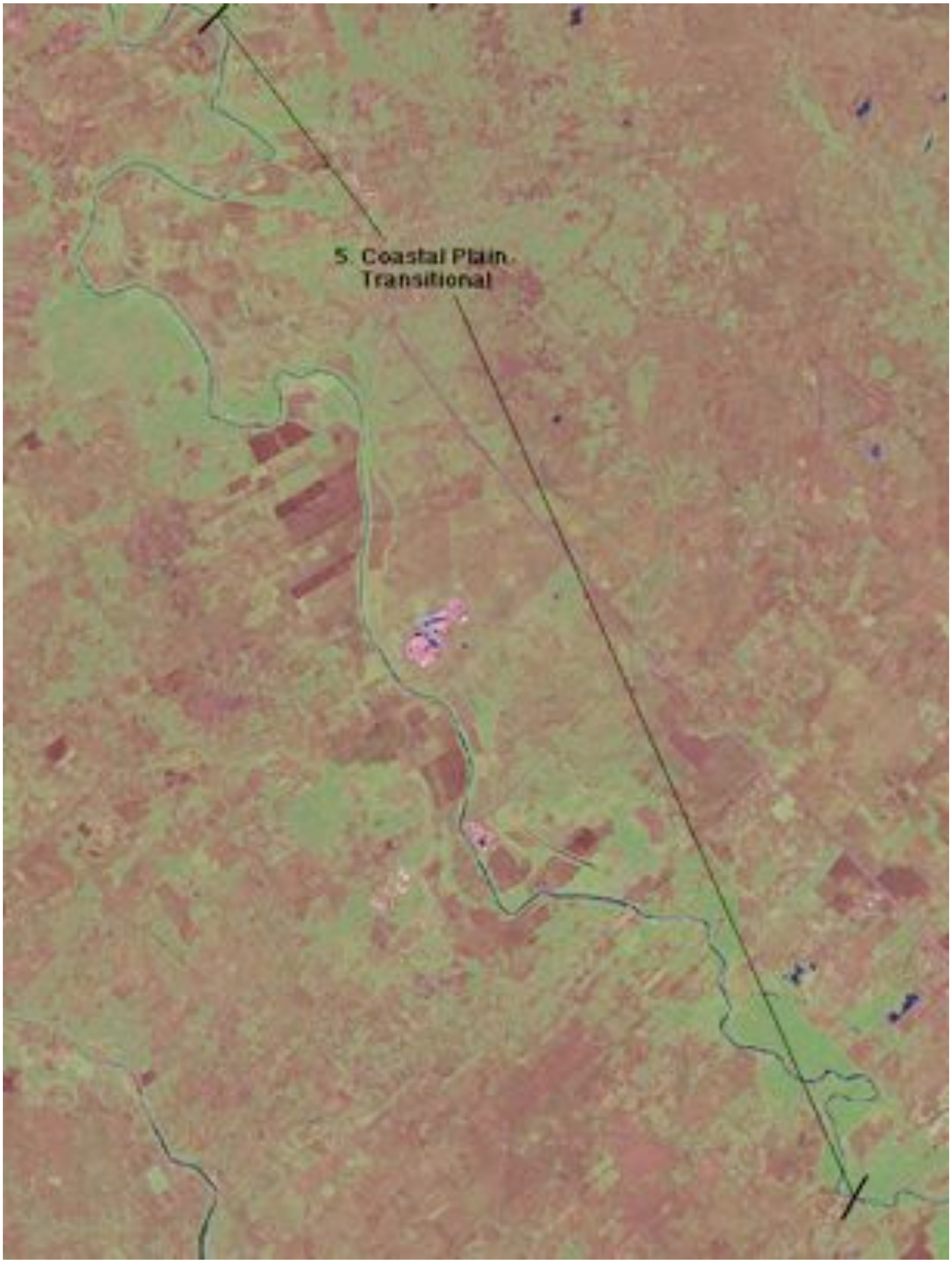

Figure 20. Zone 5, shown on a LANDSAT satellite image. Zone boundaries are indicated with black bars.

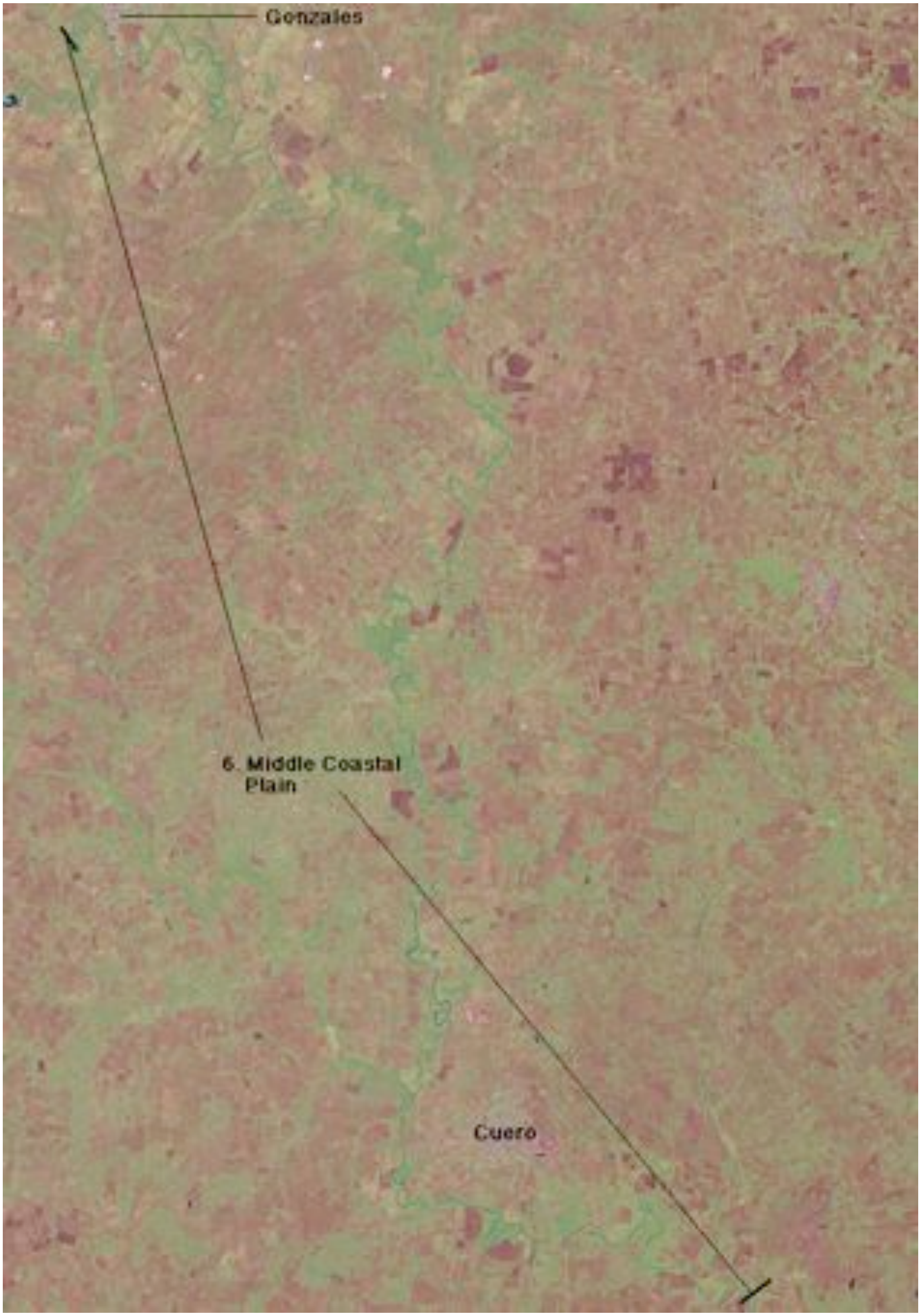


Figure 21.  Zone 6, shown on a LANDSAT satellite image. Zone boundaries are indicated with black bars.

*7. Upper Coastal Plain*

The upper end of this reach is taken as the transition from a confined to partly confined valley. Slope and sinuosity are similar to zone 6; while valley width is generally narrower and less variable than in zone 6. The geological framework is the Carrizo Sand and Recklaw formations (Eocene). CFC is moderate, due to relatively low floodplains. Discharge is dominated by spring inputs via the Comal River, and releases from Canyon Dam. Several small hydroelectric dams operated by the GBRA occur in zones 6-9 (figure 22).

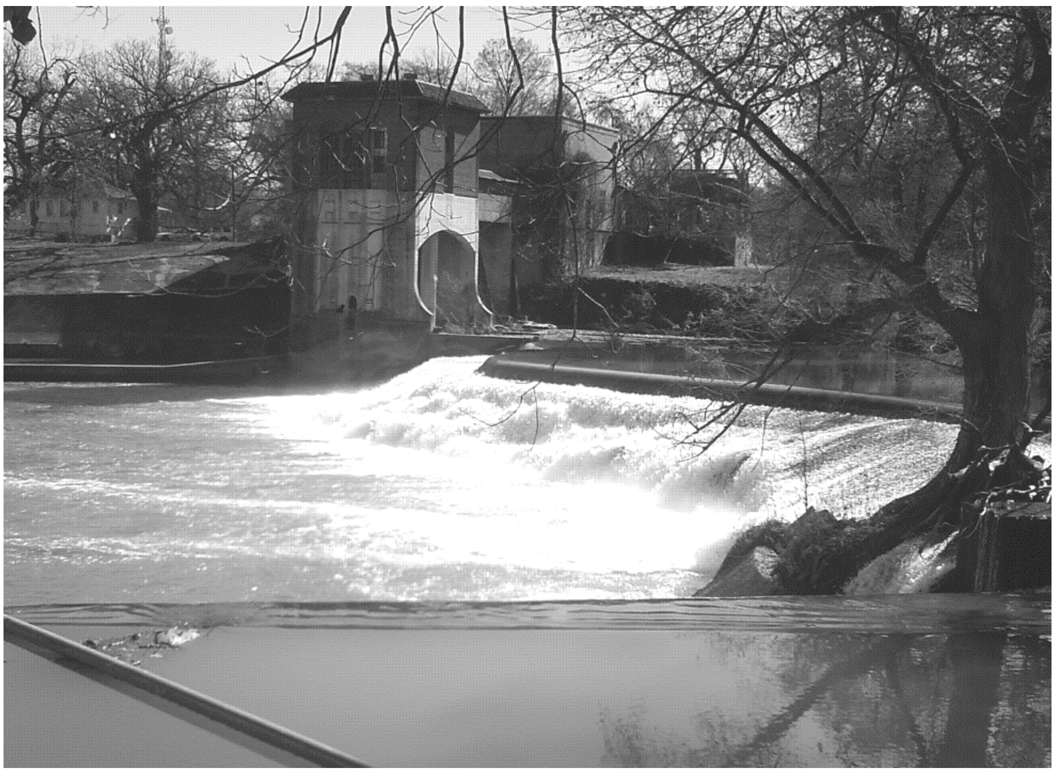

Figure 22. Hydroelectric dam on the Guadalupe River at Seguin in zone 9.

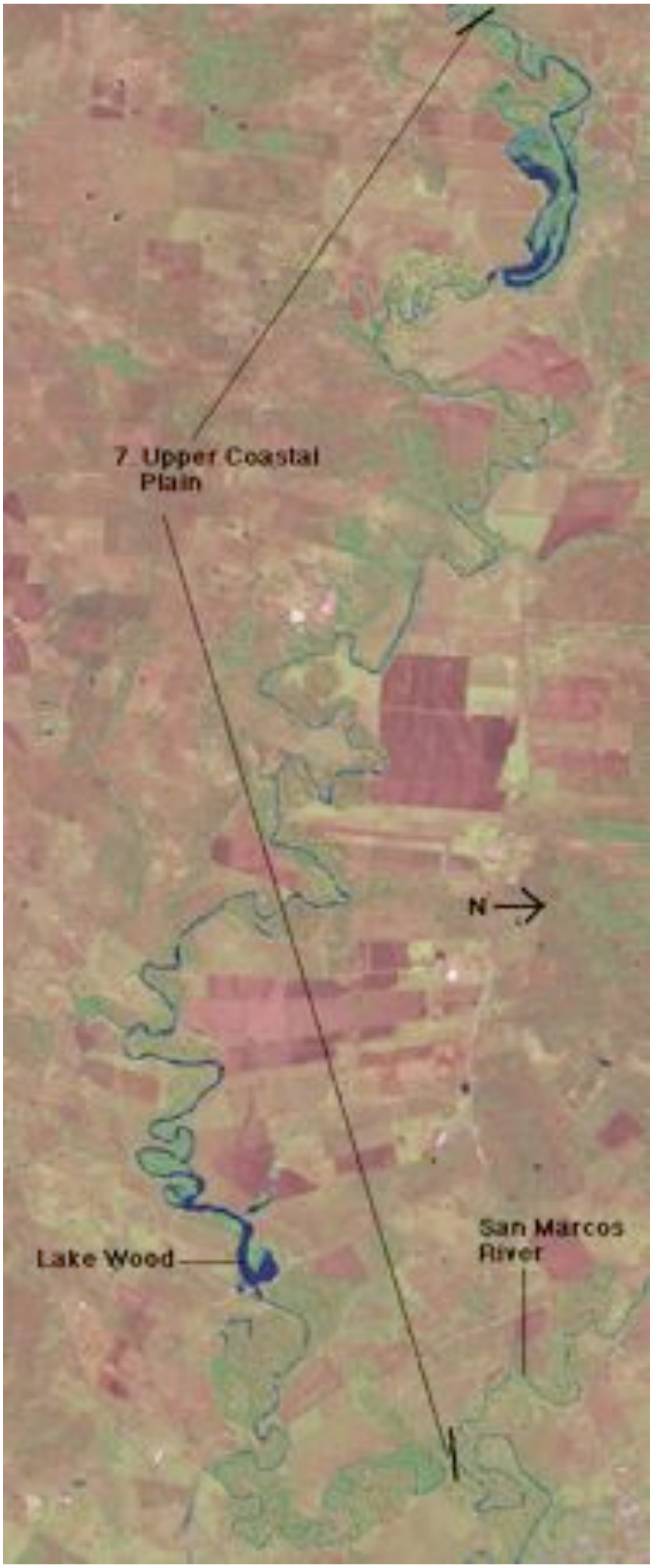


Figure 23. Zone 7, shown on a LANDSAT satellite image. Zone boundaries are indicated with black bars.

*8. Belmont Fault Zone*

The upstream end of Zone 8 is identified where the Eocene Wilcox group gives way to the Carrizo Sand and Recklaw formations. This short (25 km) zone is marked by geologically controlled variation. At the upper end valley widening occurs in connection with the outcropping of the relatively less resistant Carrizo Sand formation, while further downstream a valley constriction occurs associated with the Recklaw Formation. This river style includes the mapped fault zone near Belmont, where several straight segments of the river channel occur, either normal to or aligned with the mapped fault trends occur (see figure 11, chapter 3).

*9. Escarpment-Plain Transition*

Zone 9 encompasses the area from the base of the Balcones escarpment to zone 8. Spring flow—especially from Comal Springs, at the base of the escarpment and delivered to the Guadalupe River via the Comal River, is particularly important here. Other springs, such as Hueco Springs, at the base of the escarpment are also important. This reach is also significantly influenced by Lake McQueeny between New Braunfels and Seguin. Channel slope is the steepest downstream of the escarpment. The transition from Cretaceous geology (Fredericksburg Group on the valley rims, and Glen Rose exposed within incised valleys) to the Eocene Wilcox formation occurs within this zone. Connectivity is low to very low due to high banks and infrequent overbank flow. The river banks in zones 9, 10, 12, and 13 are often lined with bald cypress (*Taxodium distichum*) as shown in figure 25. These are important aesthetic features connected to a vibrant ecotourism industry between Kerrville and New Braunfels based on tubing, canoeing, and kayaking. The buttressing of the banks by cypress also increases bank resistance and reduces lateral channel mobility.


Figure 24. Zone 8, shown on a LANDSAT background. Zone boundaries are shown by black bars.


Figure 25.  Guadalupe River in New Braunfels in zone 9.

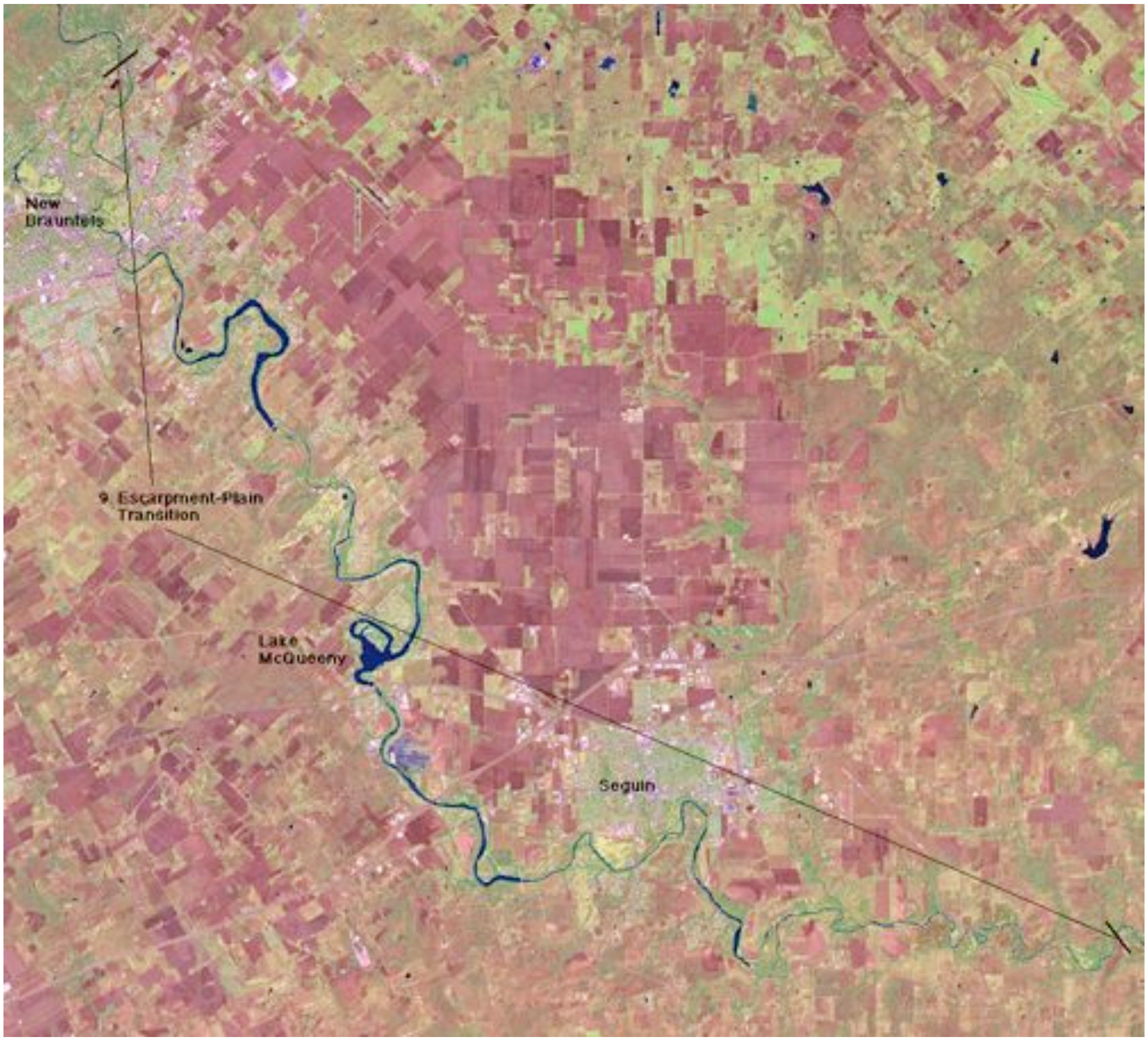

Figure 26.  Zone 9, shown on a LANDSAT satellite image. Zone boundaries are indicated with black bars.

*10. Guadalupe River Gorge*

The river gorge or canyon descends the Balcones escarpment from Canyon Dam to New Braunfels. This confined reach is the steepest in the watershed, and is characterized by a bedrock-controlled valley and channel, and numerous rapids. Significant spring inputs occur, but flows are overwhelmingly dominated by dam releases. This reach receives intense recreational use by tubers.

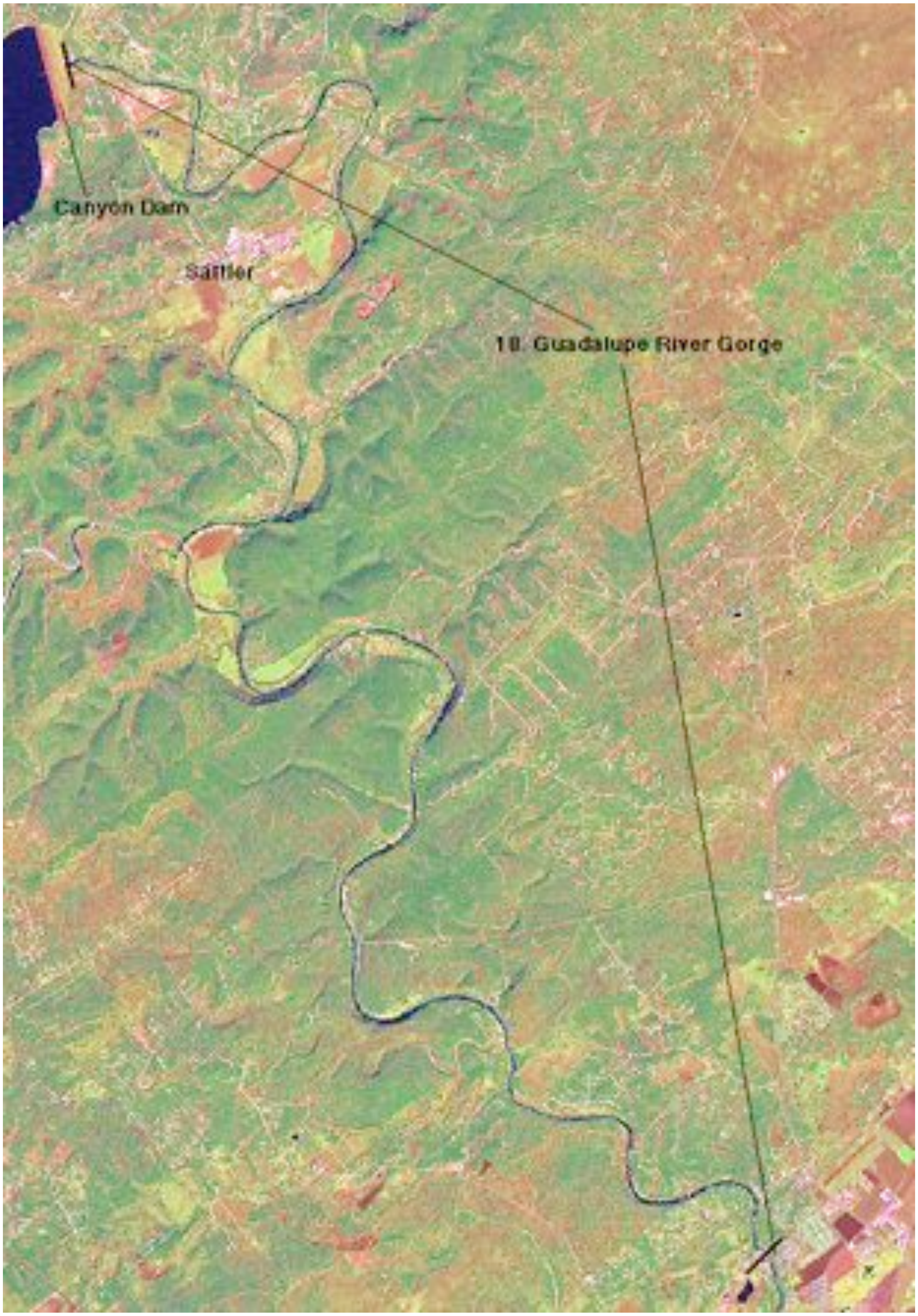

Figure 27.  Zone 10, shown on a LANDSAT satellite image. Zone boundaries are indicated with black bars.

*11. Canyon Lake*

This zone includes the lake itself, and a short section of river upstream which is dominated by backwater effects of the lake.

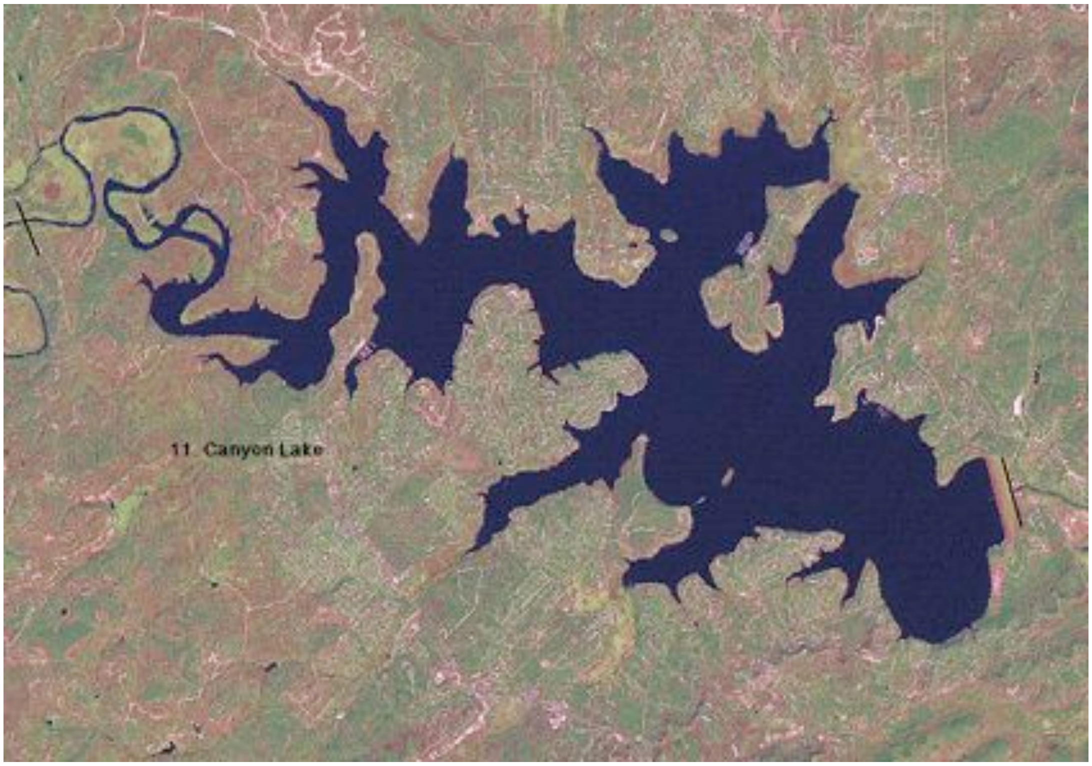

Figure 28. Zone 11, shown on a LANDSAT satellite image. Zone boundaries are indicated with black bars.

*12. Lower Plateau*

The lower (Edwards) Plateau zone begins downstream of Comfort and runs to the Canyon Lake backwaters. The slope is steep, and the channel bedrock-controlled, though with alluvial covers ranging from fines to boulders in various locations. The confined valley is relatively narrow, and CFC is very low due to the incised valley and high banks (figure 29). Formations of the Fredericksburg Group dominate the uplands, but valley incision has exposed the Hensell Sand or the Glen Rose formation. As compared to zone 13, abrasion is more and solution less important in channel incision (see chapter 3; figure 12).

Figure 29. Guadalupe River State Park, in zone 12. Note the incision as indicated by the cliffs to right, and the rounded rock fragments on the bar at left.

Figure 30. Rounded rock fragments in alluvium in zone 12, indicating gravel transport and abrasion.

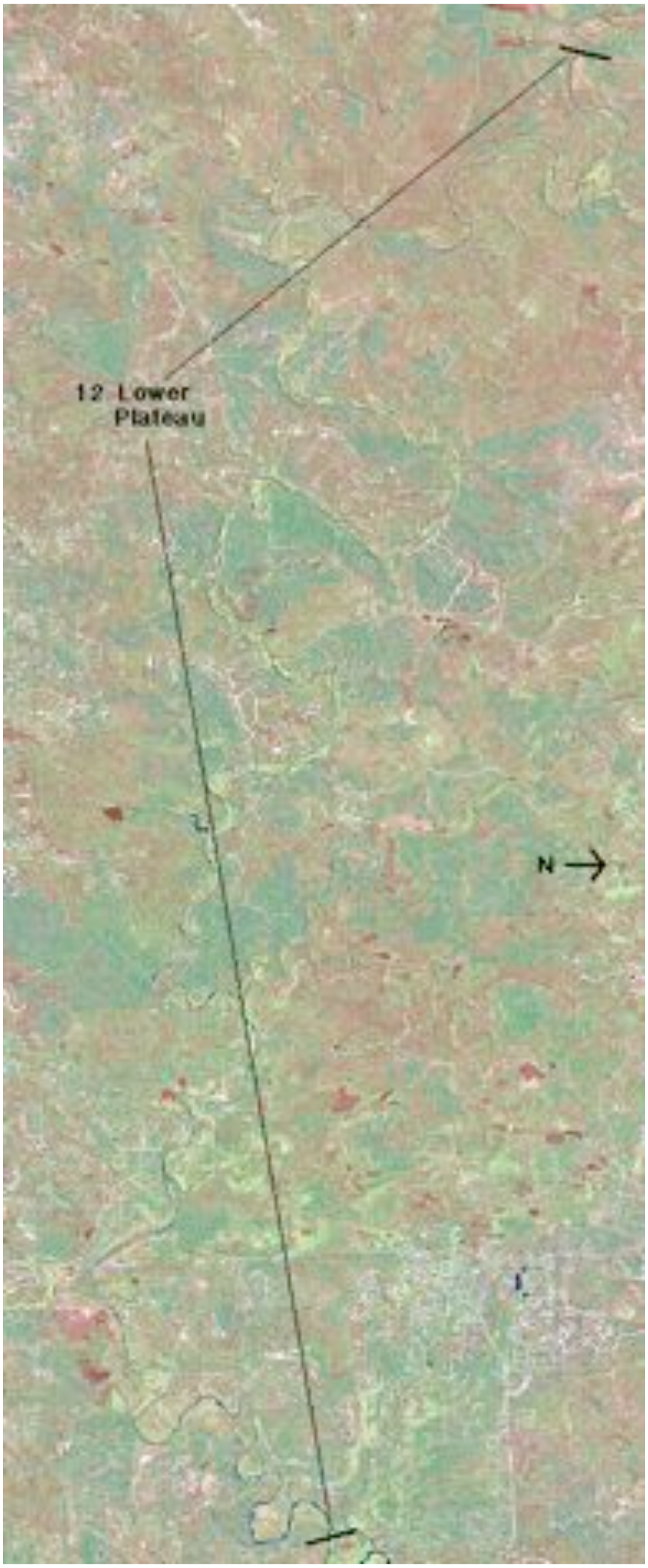


Figure 31. Zone 12, shown on a LANDSAT background. Zone boundaries are shown by black bars.

*13. Upper Plateau*

This reach begins upstream of Kerrville and extends to zone 12. This zone is characterized by a steep, bedrock-controlled channel. The nature of the exposed bedrock, the rarity of rounded clasts, and algal coatings within the channel indicate a greater importance of solution in this reach than elsewhere in the basin (figure 32). CFC is very low upstream of Kerrville, but low in the remainder of the reach due to relatively lower, flatter topography inside meander bends. Kerrville Lake and a series of low-head dams influence channel flows in this reach.

Figure 32. Guadalupe River in Zone 13, near Center Point. Note the exposed bedrock, angular rock fragments, and cypress-lined banks.

Figure 33. Relatively thin alluvial covers over bedrock occur in zone 13, as in this reach upstream of Comfort, but are more common in zone 12. Note the angularity of the rock fragments and cypress-lined banks.


Figure 34. Zone 13, shown on a LANDSAT background. Zone boundaries are shown by black bars.

# Chapter 5
# Summary and Discussion

## MANAGEMENT CHALLENGES

Management of instream flows--and water and riparian resources in general--in the Guadalupe River presents some atypical challenges. In 2002, the private organization American Rivers named the Guadalupe one of America's most endangered rivers, citing a significant amount of water diversion and what the organization termed the lack of any commitment to maintain sufficient river flows (a situation the TIFP program is intended to address). In addition to a high level of use and demand for water, management efforts are complicated by the fact that the Guadalupe River, San Antonio River, and Edwards Aquifer are managed by separate authorities.

Beyond these consumptive uses, the Guadalupe River receives intensive recreational use, particularly in geomorphic zones 9-12. With the exception of Canyon Lake itself, the local, regional, and national popularity of this area for activities such as tubing, rafting, canoeing, and kayaking is dependent not only on sufficient reliable flows of clean water, but also on maintenance of the fundamental geomorphic characteristics of the channel and river corridor.

It is not unusual for river basins the size of the Guadalupe to show significant variability in hydrology and runoff production, but the differences in the Guadalupe are more striking and profound than in most rivers. This is due to the strong dominance of karst and fluviokarst processes on the Edwards Plateau and Balcones escarpment, and the significant input of spring-fed rivers further downstream. Flow in the Guadalupe River is also very strongly influenced by a single facility--Canyon Lake and Dam. Canyon Lake is, in turn, essentially a byproduct of a unique combination of climatological, topographic, and hydrologic-response characteristics that combine to produce a propensity for large floods (see chapter 1).

As for other rivers draining to the coast, the maintenance of freshwater inflows to estuaries is an important and sometimes contentious issue for the Guadalupe River. The Guadalupe, however, strongly influences the estuary-wetland complex that comprises the winter home of the last surviving population of whooping cranes, a highly charismatic endangered species that helps support an important nature and ecotourism industry in the Texas Coastal Bend area.

## CONTROLS OF GEOMORPHIC ZONATION

The controls of the geomorphic zonation and river styles of the Guadalupe River can be divided into three general categories: extrinsic, intrinsic, and anthropic (see Phillips, 2010). Extrinsic factors are natural (non-human) phenomena that provide boundary conditions or external forcings of the fluvial system. These factors generally change slowly, if at all, over time scales relevant to river management, and are not significantly affected by the fluvial system. Intrinsic factors represent forms, processes, feedbacks, and interactions within the fluvial system. Intrinsic factors may change relatively rapidly, and are generally influenced by each other as well as extrinsic and anthropic factors. The latter are human actions (or the results thereof) that may influence fluvial systems directly (e.g. dams, diversions) or indirectly (e.g., land use change that influences runoff and sediment input).

Four major extrinsic factors influence the Guadalupe River. Broad-scale physiography defines fundamental topographic and hydrologic differences between the Edwards Plateau (zones 11-13), Balcones Escarpment (zones 9-10), Coastal Plain (zones 4-9) and Delta (zones 1-3). Geology at a finer scale is a second important intrinsic factor, independently of its relationships with physiography. Differences among zones within the major landscape units are defined by differences in the valley-bounding geology, geologic constraints on factors such as valley width and confinement, and specific tectonic features.

A third major external factor is sea level change, which in the contemporary and Holocene context means sea-level rise. This influences the Guadalupe/San Antonio Bay estuarine complex, and the delta and lower coastal plain zones (1-4). However, these effects can be expected to propagate upstream over time. Relatively rapid change could occur when the associated aggradation is able to ascend the tectonic feature at the head of the delta (boundary between zones three and four), analogous to what Rodriguez et al. (2005) documented from the stratigraphic record in the Galveston Bay area. Climate is also an extrinsic factor, though (like sea-level) it is indirectly influenced by human actions. In terms of river zonation, climate is indirectly reflected via a general upstream-downstream gradient of increasing precipitation. Ongoing climate change poses a major challenge for resource management in the Guadalupe River basin (and in essentially all others as well).

Intrinsic factors include a wide variety of interrelationships among flow hydraulics, sediment transport and storage, channel and valley morphology, and geomorphic units within the river styles or zones. These are significant factors in defining differences in, for instance, the different channel erosion styles of zones 12 and 13, and variations in slope and sinuosity differentiating zones 2-9. Intrinsic factors are also the major harbingers of change in the fluvial system. For example, rising sea level or changes in water and/or sediment input to zones 1-4 will be reflected first in factors such as sinuosity, meander growth or cutoffs, avulsions, and channel slope.

Human agency is pervasive in the Guadalupe River basin (as in many U.S. watersheds), with a variety of both direct and indirect impacts. The key anthropic factors directly affecting the geomorphic zonation are Canyon Lake, low-head dams in both the Edwards Plateau and Coastal Plain landscape units, and hydrologic modifications in the delta area. Canyon Lake and Dam are directly responsible for zone 11. Dam releases significantly influence all downstream zones (1-10), with the effects become progressively less further downstream. The low-head dams differentiate zones 12 and 13 in part, and are a significant characteristic of zones 6-8. The saltwater barrier and diversion canal near

Tivoli differentiates zones 1 and 2, but water control features and artificial channels are pervasive throughout the delta (zones 1-3).

Intrinsic factors are inherently dynamic, as are human impacts, which respond to not only environmental forcings and controls, but also to economic, social, and political changes. Extrinsic factors are to some extent fixed (physiography and geology) and mostly beyond direct human manipulation (climate and sea level). However, climate and sea level are dynamic and undergoing historic and contemporary change. Because of this, the geomorphic zones or river styles of the Guadalupe should be viewed as variable rather than static features. The general sequence and location of zones will persist for decades, at a minimum, in the absence of anything other than catastrophic environmental events or drastic human actions. However, the specific locations of the zone boundaries, and the characteristics of the zones themselves, are subject to change.

## Acknowledgements

Greg Malstaff of the Texas Water Development Board provided important support for this project, both in the scientific/technical and administrative realms. Jidan Duan and Jeff Levy (University of Kentucky) provided critical and expert assistance with assembling the GIS databases.

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# Appendix: Scope of Work

SCOPE OF WORK PLAN
*Geomorphic Processes, Controls, and Transition Zones in the Guadalupe River*

Overview

This work plan addresses a cooperative research study of the geomorphology of the Guadalupe River, Texas, from Kerr County to Guadalupe Bay. The study will delineate major geomorphic process zones, with an emphasis on stream energetics as indicated by stream power and shear stress; identify major geomorphic controls (including karst hydrogeology, sea level and climate change, and antecedent topography); and determine the location and primary controls over key "hinge points" or transition zones.

The specific objectives are to:

(1) Develop a baseline characterization of the condition and behavior of the Guadalupe River.

(2) Examine longitudinal (downstream) changes in flow processes and energetics, channel and valley morphology, and patterns of recent geomorphic change.

(3) Classify the Guadalupe (based on items 1, 2) into geomorphic process zones.

(4) Identify the primary controls—both contemporary and historic—of the geomorphic process zones.

(5) Identify the current location, primary controls over, and potential future changes in critical transition zones.

Deliverables will include a report covering the objectives above, and maps (hardcopy and digital) of the process and key transition zones.

Methods

*Baseline Characterization* at broad river scales will establish the geomorphic framework of the river in terms of geology, topography, hydrology, soils, and land/water use. The major data sources will be:

- 1:250,000 scale geologic maps from the Texas Bureau of Economic Geology.
- Digital elevation models obtained from the U.S. Geological Survey Data Distribution Center.
- Discharge and stage data from U.S. Geological Survey gaging stations.
- Soil surveys from the Natural Resources Conservation Service in the form of published surveys for counties within the study area, or obtained via the NRCS web soil survey data distribution program.

- 1-m and 2.5-m resolution digital orthophotoquads (DOQQ) from the Texas Natural Resources Information System (TNRIS) and the Lousiana statewide GIS.
- 1:24,000 topographic maps in DLG (digital line graph) form from TNRIS.

*Current Geomorphic Condition* assessments will be made using the data sources listed above. The current condition assessment will describe the contemporary state of the reach based on factors such as the degradational or aggradational state of the channel, frequency of overbank flooding, lateral migratory stability, typical range of flows, presence or absence of diagnostic geomorphic features (for example knickpoints, cut banks, point bars, tributary-mouth bars or deltas, oxbows, and meander scars), and morphometric properties (for example valley vs. channel width ratio, channel sinuosity, valley slope).

Specific criteria to be assessed based on the digital, archival, and field data include:

- Channel sinuousity, which may reflect upstream limits of effects of Holocene sea level rise (Phillips et al. 2005; Phillips 2007b; Phillips and Slattery 2007b).
- Channel thalweg elevation relative to sea level and reservoir pool elevations.
- Channel and water surface slopes.
- Discharge, stream power, and shear stress at gaging station locations for reference flows (mean daily discharge exceedence probabilities of 1, 10, and 50 percent; bankfull discharge; the flood of record; and selected high flow events).
- Evidence for tidal, coastal, and lake backwater influences.
- Transition from convergent to divergent flow network (see Phillips and Slattery, 2006; Phillips 2007b).
- Ratios of valley, modern floodplain and channel widths and width/depth ratios.
- Presence and mobility of sandy point bars.
- Evidence for channel incision/aggradation or widening/narrowing.
- Evidence for active floodplain and valley accretion (or erosion).
- Presence of remnant Quaternary alluvial terrace surfaces identified in previous studies in central and southeast Texas, and other antecedent morphological features.
- Influence of karst hydrology and topography.
- Presence and size of Quaternary paleomeanders (which reflect previous flow regimes and may influence contemporary geomorphology and hydrology).

Specific techniques will be similar to those used in recent and ongoing studies by the principal investigator and coworkers in the Sabine, Trinity, and Brazos Rivers and Loco Bayou, Texas (Phillips 2001; 2003; 2007a; 2007b; Phillips et al. 2004; 2005; Phillips and Marion 2001; Phillips and Slattery, 2006; 2007a; 2007b; Wellmeyer et al. 2005).

**Geomorphic Processes, Controls, and Transition Zones in the Guadalupe River**
**Draft-final report to the Texas Water Development Board**

Contract number 0904831034

## REQUIRED CHANGES

### General Draft Final Report Comments:

1. Please correct the following typos:
    a. Page 9, 2nd paragraph, "Calciustolls in underlain" should be "Calciustolls underlain."
    b. Page 11, Table 1, 5th paragraph, "Area$^{a}$" should be "Area$^{b}$."
    c. Page 12, 1st paragraph, "Ths pumps abundant" should be "This pumps abundant."
    d. Page 14, 2nd paragraph, "obtained from he" should be "obtained from the."
    e. Page 21, 1st paragraph, "ratios of flood to median discharge (Table 3)" should be "ratios of flood to median discharge (Table 4)."
    f. Page 21, 2nd paragraph, "in the lower coastal plain and delta (Table 3)" should be "in the lower coastal plain and delta (Table 4)."
    g. Page 21, 4th paragraph, "orginated" should be "originated."
    h. Page 22, 1st paragraph, "area has received" should be "area had received."
    i. Page 22, 1st paragraph, "In the the Guadalupe" should be "In the Guadalupe."
    j. Page 22, 2nd paragraph, "duing this event" should be "during this event."
    k. Page 22, Table 5, "peaks at gaging at gaging" should be "peaks at gaging".
    l. Page 22, Table 5, "Time difference/Distance (km hr$^{-1}$)" should be "Distance/Time difference (km hr$^{-1}$)."
    m. Page 23, 3rd paragraph. The abbreviation NWS was introduced on the previous page. Therefore, "according to National Weather Service (NWS) measurements" should be "according to NWS measurements."
    n. Page 2, Table 6, "Time difference/Distance (km hr$^{-1}$)" should be "Distance/Time difference (km hr$^{-1}$)."
    o. Page 2, Table 6, "Gonzo-Cuero" should be "Gonzales-Cuero."
    p. Page 26, 1st paragraph, "W  is reduced" should be "Stream power  is reduced."
    q. Page 27, 1st "Ω  increases rapidly" should be "stream power  increases rapidly."
    r. Page 28, 1st paragraph, "Ω  for the flood discharge" should be "stream power for the flood discharge."
    s. Page 35, Table 14, "sources orginating below" should be "sources originating below."
    t. Page 39, 2nd paragraph, "Point 12 is colocated" should be "Point 12 is collocated."
    u. Page 42, 4th paragraph, "in the vicnity of" should be "in the vicinity of."
    v. Page 43, 2nd paragraph, "landsape units" should be "landscape units".
    w. Page 55, 1st paragraph, "end of the this reach" should be "end of this reach."

x. Page 57, 2nd paragraph, "as shown in figure X" should be "as shown in figure 25."
y. Page 60, 1st paragraph, "Signficant spring" should be "Significant spring."
z. Page 69, 3rd paragraph, "analagous" should be "analogous".

2. There are a few differences between the data provided in Table 1 on page 11 of the report and data available from TWDB ( http://wiid.twdb.state.tx.us/ims/resinfo/viewer.htm? ). Specifically, according to TWDB data, the year of completion of Lake Dunlap is 1928 while 1931 is listed in Table 1. Also, according to TWDB data the volume of Lake Gonzales should be 6,500 ac-ft while Table 1 lists a value of 7,500 ac-ft. Please insure these differences are not typos. If they are not typos, please provide the source for this data.
3. On page 14, 4th paragraph, the report states that "Perkin and Bonner (2010) found that the number of small and large floods increased slightly (from about 0.81 to 1.07 per year) in the upper Guadalupe River". Later in the paragraph, the following statement is made: "However, given the slight decrease *(in floods per year)* in the upper river …" These statements seem contradictory. Please modify or provide additional information that explains these statements.
4. On page 24, 3rd paragraph, the report provides distances between several stream flow gages. These are different from those obtained from the gage descriptions in the USGS's Water Year Reports. Please describe the data source and/or method used to calculate the distances between gages. Also, the value provided for the distance between gages on page 24 is different from what can be determined from the distances downstream provided in Table 7 on page 26. Please double check calculations for these distances, resolve any differences, and update values for mean velocity (Table 6, page 24) and stream power (Table 7, page 26) as necessary. The differences in distance are shown in the table below:

| Segment | Distance (km) from page 24 | Distance (km) determined from Table 7, page 26 |
|---|---|---|
| New Braunfels to Seguin | 56 | 117 |
| Seguin to Gonzales | 117 | 117 |
| Gonzales to Cuero | 117 | 97 |
| Cuero to Victoria | 97 | 28 |
| Victoria to Tivoli | 57 | n/a |

5. On page 31, 1st paragraph, the report states "Other than the lower 48 mi (78 km), the river downstream of the Balcones Escarpment is mainly partly confined (zones 2, 4, 6), with relatively short (9 to 11 mi) confined reaches." Based on the data presented in Table 11 on the same page, the "relatively short confined reaches" (namely zone 3 and 5) have lengths of 11 and 16 miles respectively. Please correct the text to reflect these lengths or provide an explanation of why the lengths appear different when calculated from the distances provided in Table 11.
6. The following sentence on page 69, 2nd paragraph, is confusing: "The valley-bounding geology, geologic constraints on e.g., valley width and confinement, and specific tectonic features help define differences among zones within the major landscape units." Please modify to make the meaning clear.

**SUGGESTED CHANGES**

7. On page 29, the example of Zone 3 in the caption to Table 8 is difficult to understand. Consider rephrasing to the following: "Thus zone 3, for instance, begins 130 km (81 mi) upstream of the bay and ends 287 km (178 mi) upstream of the bay."
8. Throughout the document, the abbreviation for cubic feet per second is given as "cfs." To be consistent with that format, consider making the following changes:
    a. On page 33, 1st paragraph, "about 9,000 $ft^3$ $sec^{-1}$" should be "about 9,000 cfs."
    b. On page 50, 1st paragraph, "< 3000 $ft^3$ $sec^{-1}$" should be "< 3000 cfs."
9. To maintain consistency, please consider referring to portions of river delineated by the geomorphic zonation process exclusively as "Zones" throughout the document. If this format is adapted, references to "River Style 8" and "River style 9" on page 57 should be replaced with "Zone 8" and "Zone 9", respectively. Also, references to "river style" on pages 62 and 65 should be replaced with "Zone."

**RESPONSE TO COMMENTS ON DRAFT FINAL REPORT**

All corrections and suggestions have been accepted and incorporated into the final report.