Geomorphic Processes, Controls, and Transition Zones in the Middle and Lower Trinity River

Project Report for the Texas Water Development Board and Texas Instream Flow Program, TWDB contract number 0704830781

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INTRODUCTION

This report conveys the results of a study of the geomorphology of the Trinity River, Texas, from the confluence with the Elm Fork near Dallas to Trinity Bay. The study was designed to delineate major geomorphic process zones, with an emphasis on stream energetics as indicated by stream power; to identify major geomorphic controls (including 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 in the project scope of work were to:

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

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

(3) Classify the middle and lower Trinity (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 both affects and reflects hydrology. The type and quality of aquatic and riparian habitats are directly related to specific landforms and geomorphic processes (e.g., Hupp and Osterkamp, 1996; Scott et al., 1996; Robertson and Augspurger, 1999; Johnston et al., 2001; Gumbricht et al., 2004; Moret et al. 2006). There is little dispute of this contention. Statements such as Montgomery's (1999), for example, that "spatial variations in geomorphic processes govern temporal patterns of disturbances that influence ecosystem structure and dynamics," have never been seriously challenged. 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). Geomorphology is also critical to classification, delineation, and impact analysis of wetlands. U.S. government agencies charged with wetlands regulatory and assessment programs, for example, 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--even 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 includes the lower and portions of the middle Trinity River basin (Figure 1), from the confluence of the main fork of the Trinity and the Elm Fork southeast of Dallas, to Trinity Bay (a portion of Galveston Bay).

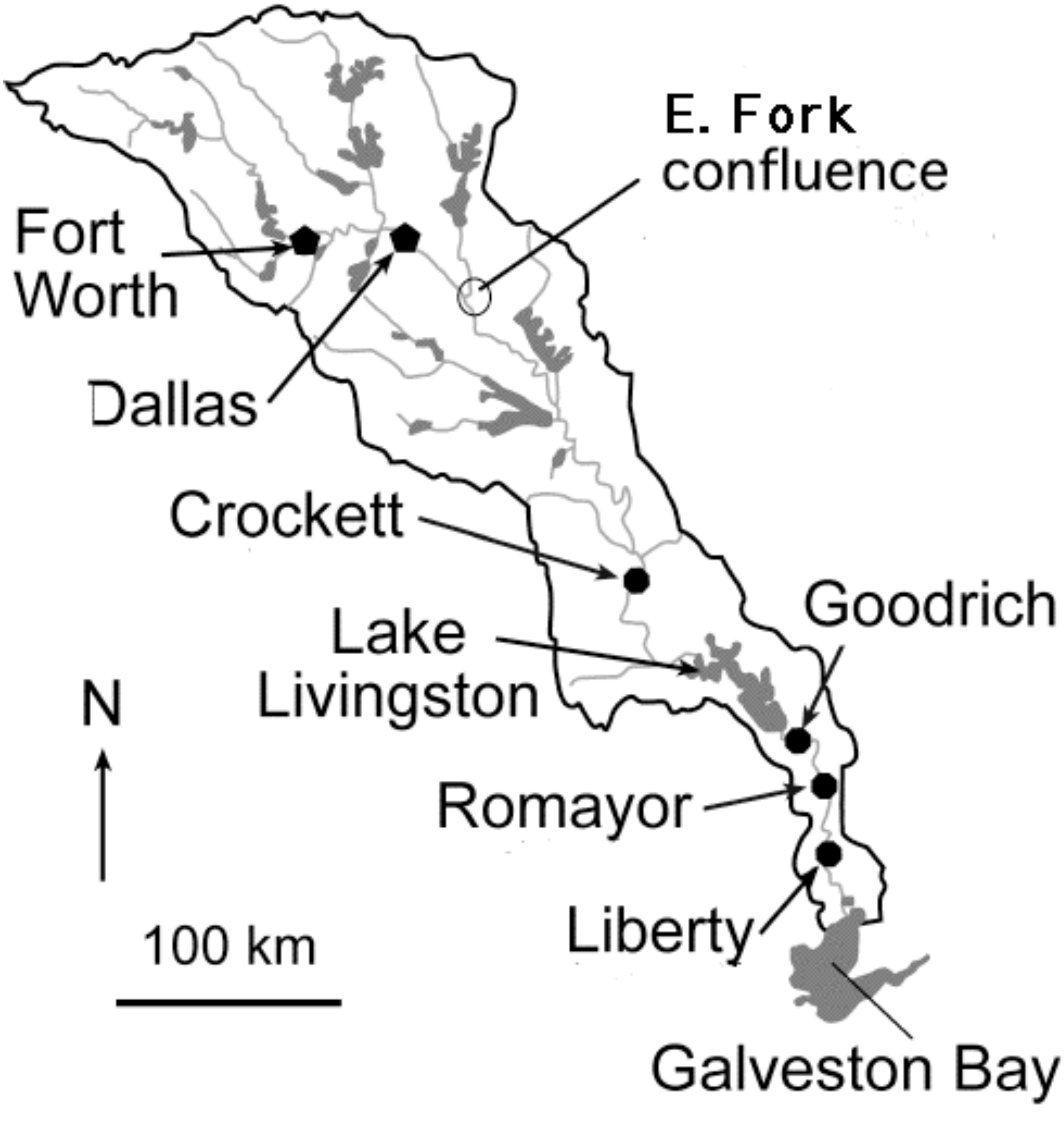


Figure 1. Trinity River basin, with some key reference points. The study area is from the Elm Fork confluence to Trinity Bay at the head of Galveston Bay.

The area includes portions of five major land resource areas (MLRA) as defined by the U.S. Department of Agriculture. The upper end of the study area is in the Blackland Prairie region (Figure 2), characterized by nearly level to gently rolling topography, and fertile soils with high proportions of smectitic clays. Much of this area was once cultivated, but significant amounts of cropland have been converted to pasture, and urban land uses dominate the Dallas-Fort Worth area just upstream of the study reach. South of the blacklands, especially on the west side of the watershed, the Texas Claypan area extends down to the Lake Livingston area. Clay-rich, smectitic subsoils and level to gently sloping topography, except where entrenched by streams, characterize this area. The east side of the watershed, south of roughly 32° N to south of Lake Livingston, is in the Eastern Timberlands MLRA, as is much of the western portion of the basin downstream of Lake Livingston. Extensive forest cover, including many commercial forests, is the dominant land cover. The lowermost portion of the Trinity watershed is in the Coastal Prairie and Marsh MLRA, with flat topography, generally poor drainage, and and a natural vegetation of marshes and prairies with some forest stands.

The Bottomlands MLRA runs through the entire study area, including the Trinity River valley itself and the lower valleys of major tributaries. This includes the active floodplain and Quaternary alluvial terraces.

The climate is humid subtropical, and almost all precipitation falls as rain. Most streams are perennial, but summer droughts are relatively common. Mean annual precipitation ranges from about 900 mm yr^{-1} in the upper portion of the study area to more than 1300 mm yr^{-1} in the lowermost basin, generally increasing in the upstream-downstream direction.

The Trinity River basin includes 33 reservoirs with more than 10,000 acre-feet (1.23×10^7 m^3) of storage, and hundreds of smaller lakes, ponds, and tanks. Lake Livingston, with a capacity of more than 1.7 million ac-ft (2.14×10^9 m^3) is the largest and downstream-most. Lake Livingston is also the only impoundment along the main stem of the river within the study area.

The Trinity River valley is entrenched into a variety of geologic formations ranging from Cretaceous to late Quaternary, these formations comprising the surficial geology of the valley walls and watershed outside the alluvial valley. Generally upstream to downstream, the bounding formations are late Cretaceous, Paleocene, Eocene, and Miocene to approximately Lake Livingston. Further downstream the geology framework is Quaternary. The river valley itself is composed of recent (Holocene) active floodplains and earlier Quaternary alluvial terrraces. The general Quaternary geomorphic history in the lower basin is discussed by Blum et al. (1995) and Phillips and Slattery (2008).

More information on the general environmental setting on the Trinity River watershed is provided by Land et al. (1998).

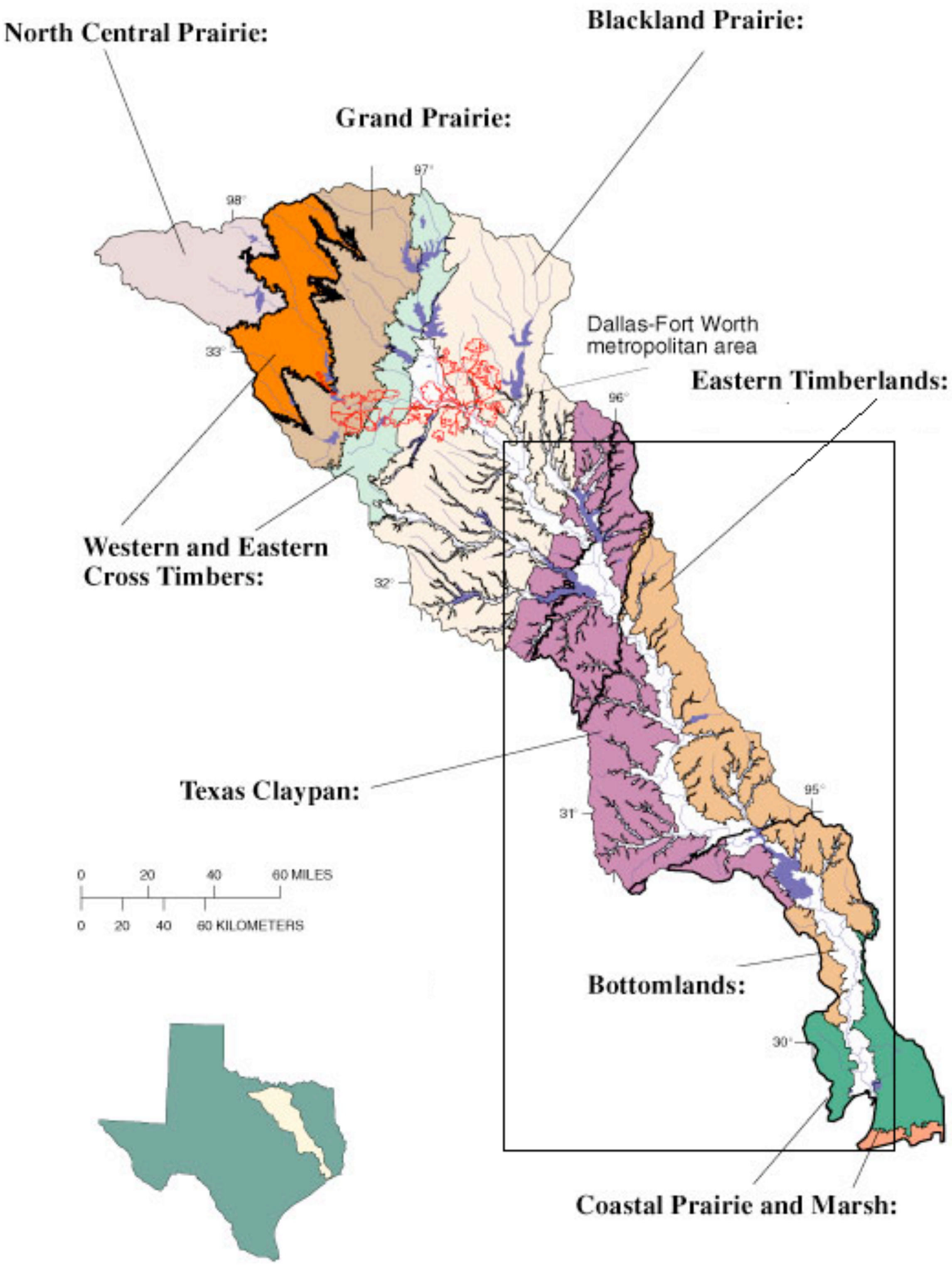


Figure 2. Trinity River drainage basin, showing major land resource areas. Study area is shown in the box. Map adapted from Land et al., 1998.

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). The river from Lake Livingston to Trinity Bay has also been extensively examined in the field by the author and collaborators in a series of previous projects (Phillips and Musselman, 2003; Phillips, et al., 2004; 2005; Phillips and Slattery, 2007; 2008; Phillips, 2008; Wellmeyer et al., 2006; Musselman, 2006).

Digital elevation data (DEMs) at a 30 m resolution was extracted from the NED (National Elevation Dataset) from the U.S. Geological Survey. Digital ortho quarter quads (DOQQs), color aerial photography taken in 2004, were obtained from he 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. Stream networks and hydrologic unit delineations were obtained via the USGS NHD (National Hydrographic Dataset). Discharge data was obtained for nine 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

Based on initial reconnaissance and preliminary data analysis, and experience in similar work on the Sabine and Brazos Rivers (Phillips and Slattery, 2007; Phillips, 2006; 2007; 2008) potential geomorphic controls and indicators were identified. The study reach was then subdivided on the basis of each of these, and the boundaries compared (boundary coincidence analysis; BCA).

Six criteria were selected for BCA: slope, sinuosity, valley width, valley confinement, channel-floodplain connectivity, and geology. Hydrologic information was also considered in determining zonations, but as this is available only a selected points, it was not directly included in the BCA.

Slope was measured from calculated channel paths in the DEM.

Sinuosity is a measure of the “curviness” of the river, and is the ratio of channel distance divided by valley distance. 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.

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.

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 Trinity River and delta area.

Geology indicates the dominant age of the formations bounding the river valley for the variety of Cretaceous, Paleocene, Eocene, and Miocene formations. For the Quaternary the dominant formation is listed (Willis, Lissie, Beaumont). Note that most of the study area contains some Quaternary alluvial terrace remnants within the valley.

In each case, the identified reaches and zones were identified by nearby prominent landmarks such as tributaries and bridge crossings, and by approximate up- and downstream distances from Trinity Bay or the Elm Fork.

Chapter 2
Flow Regimes

GAGING STATIONS

Information on flow regimes in the study area comes from U.S. Geological Survey Stream gaging stations. The list of stations potentially relevant to the Trinity River within the study area is shown in Table 1. These include two stations on the Trinity and one on the Elm Fork in the Dallas area upstream of the study area. There are 11 stations on the Trinity River within the study area. However, three of these (Riverside, Moss Bluff, and Wallisville) provide only river stage or elevation (as opposed to discharge) data, and the Lake Livingston station indicates lake levels and storage only. Additionally, interpretation of data from the Liberty station is complicated by the presence of tidal backwater effects under some conditions (note that the datum is below sea level). However, as discussed by Phillips and Slattery (2007), the stage-only Moss Bluff and Wallisville stations are rare examples of monitored sites in the fluvial-estuarine transition zone of coastal plain rivers, and were used in that study to examine downstream changes in discharge, slope, and stream power.

Table 1. Stream gaging stations in the study area. Code is the U.S. Geological Survey station identification code. DS and US indicate the distance (km) downstream of the Elm Fork/Trinity confluence or upstream of Trinity Bay. Drainage area (km^2) upstream of each station and the datum (m above mean sea level NGVD29) of the gage are also shown.

Name	*Code*	*DS*	*US*	*Area*	*Datum*
Elm Fork nr Carollton[a]	08055000			6,369	131
Trinity River @ Dallas[a]	08057000			15,814	112
Trinity R. below Dallas[a]	08057410	-50.06	688.27	16,260	111.52
Trinity R. nr Rosser	08062500	13.46	624.75	21,101	90.72
Trinity R. @ Trinidad	08062700	101.29	536.92	22,113	71.78
Trinity R. nr Oakwood	08065000	185.68	452.53	33,237	53.36
Trinity R. nr Crockett	08065350	302.14	336.07	36,029	43.02
Trinity R. @ Riverside	08066000	424.39	213.82	40,375	27.39
Lake Livingston Dam	08066190	490.26	147.95	42,950	
Trinity R. nr Goodrich	08066250	506.04	132.17	43,626	12.19
Trinity R @ Romayor	08066500	540.59	97.62	44,512	7.90
Trinity R @ Liberty	08067000	574.71	63.50	45,242	-0.68
Trinity R nr Moss Bluff	08067100	603.13	35.08	45,514	-0.76[b]
Trinity R @ Wallisville	08067252	629.50	8.71	46,091	

[a] Upstream of study area.
[b] Estimated by author.

DISCHARGE

Mean daily discharge and maximum annual discharge, reported in ft^3 sec^{-1}, were examined for the stations shown in Table 2, all of which have at least 38 years of record. The overall mean and median of the daily flows was calculated and converted to m^3 sec^{-1}. Because mean values are often skewed by occasional extreme flows, the median is a better indication of typical flows, and represents the discharge with an approximately 50-50 chance of daily exceedence. Because of the backwater effects and multimodal stage-discharge relationships for the Liberty station, mean and median values are unreliable and are not reported in Table 2.

Table 2. Discharge characteristics of Trinity River gaging stations. Record indicates the earliest year of continuous records. Mean and median discharges (m^3 sec^{-1}) are based on mean daily discharge. Flood discharge is based on official flood stages for each station (see text). RI is the recurrence interval (years) for the flood discharge based on the annual maximum flow series. The "prob" column is the probability that any given day's mean flow will equal or exceed the flood discharge. The lower part shows the mean daily flows with 1-, 2-, and 5-year recurrence intervals.

Name	*Record*	*Mean*	*Median*	*Flood*	*RI*	*prob*	*Flood/ median*
Elm Fork nr Carollton[a]	1952	23.1	4.1	177.0	2.2	0.014	43.1
Trinity R. below Dallas[a]	1957	66.0	22.3	291.0	1.4	0.035	23.5
Trinity R. nr Rosser	1939	90.2	28.6	744.0	2.1	0.011	25.7
Trinity R. @ Trinidad	1969	125.6	37.7	472.9	1.2	0.056	12.6
Trinity R. nr Oakwood	1923	149.4	43.3	662.6	1.6	0.042	15.3
Trinity R. nr Crockett	1966	184.8	65.7	1230.7	2.8	0.008	18.7
Trinity R. nr Goodrich	1966	231.6	78.7	1722.8	3.3	0.005	21.9
Trinity R @ Romayor	1924	223.7	77.0	2406.9	10.6	0.001	31.2
Trinity R @ Liberty[a]	1940			909.0	1.4	0.153	

Name	*1-year*	*2-year*	*5-year*	*1-year/ median*
Elm Fork nr Carollton[a]	218.9	273.8	428.1	34.4
Trinity R. below Dallas[a]	767.4	991.1	1462	42.8
Trinity R. nr Rosser	1223.3	1535.0	2122	38.5
Trinity R. @ Trinidad	1452.7	1704.7	2101	43.7
Trinity R. nr Oakwood	1891.6	2319.2	2815	26.7
Trinity R. nr Crockett	1752.8	2092.0	2920	24.5
Trinity R. nr Goodrich	1925.6	2265.4	2859	25.2
Trinity R @ Romayor	1938.3	2314.0	2703	34.4
Trinity R @ Liberty[a]	2468.0	2807.0	2980	42.8

[a] Upstream of study area.

Median and mean discharges decrease as expected downstream from the stations upstream of the confluence to Goodrich in the lower basin. A minor decrease occurs downstream of Goodrich due to water storage on the floodplain and diversion of water at sub-bankfull flows into a high-flow anabranch which bypasses the Romayor gage. This is discussed in detail by Phillips and Slattery (2007).

Flood stages were determined from the National Weather Service Advanced Hydrologic Prediction Service (AHPS) for the Houston/Galveston and Fort Worth NWS offices (http://ahps.srh.noaa.gov/index.php?wfo=hgx; http://ahps.srh.noaa.gov/index.php?wfo=wfo). The flood level is the stage and associated discharge at which minor lowland flooding begins, and corresponds closely with overbank flow. The annual series of peak flows was used to determine the recurrence interval associated with this discharge based on the traditional formula

$$RI = (m+1)/n$$

where RI is in years, m is the rank of a given discharge event in the annual series, and n is the years of record. Recurrence intervals range from 1.2 years at Trinidad and 1.4 at Liberty and below Dallas to 10.6 years at Romayor. Table 2 shows no apparent upstream-downstream trend, and no systematic relationship between overbank flows and recurrence intervals.

The record of mean daily flows was used to determine the probability that the 24-hour averaged discharge equals or exceeds the flood discharge in a given day, based on

$$Prob(Q) = n/(m+1)$$

Where n is in this case the total number of days in the record and m the rank of the event.

Higher probabilities thus reflect not only the number of times flows go overbank, but also the duration of flooding. These probabilities vary over an order of magnitude (0.005 to 0.056) at the stations upstream of Romayor. The two lowermost stations exhibit both the lowest (Romayor) and highest (Liberty) probabilities. The greatly increased likelihood of overbank flow downstream of Romayor partly explains the sediment “bottleneck” which exists in the lower Trinity, whereby most sediment is stored as alluvium and little is delivered to the Trinity delta and bay (Phillips et al., 2004; Phillips and Slattery, 2007).

The occurrence of bankfull and overbank flows is sensitive to channel capacities and morphologies in the vicinity of gaging stations as well as to water inputs. The variations in probabilities and recurrence intervals shown in Table 2 make it clear that no consistent relationship between channel-filling flows and recurrence intervals can be assumed for the middle and lower Trinity River.

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 γ is specific weight of water.

The slope in stream power 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.

Slope gradients for the Trinity River gaging stations with established gage datums were determined in three different ways. First, the gage datums for each station (elevation above mean level relative to NGVD29) coupled with channel distances measured from aerial photographs were used to compute slopes:

$$S = (h_u - h_d)/L$$

where h_u is the datum elevation of the station upstream of the station of interest and h_d that of the station of interest, and L the distance between the stations. Gage datums are often coincident with the channel bottom, at least at the time of establishment, but may not correspond with the thalweg or any other reference point in the cross-section. Further, the distance between stations (>29 km in all cases) is farther than optimal for slope determinations.

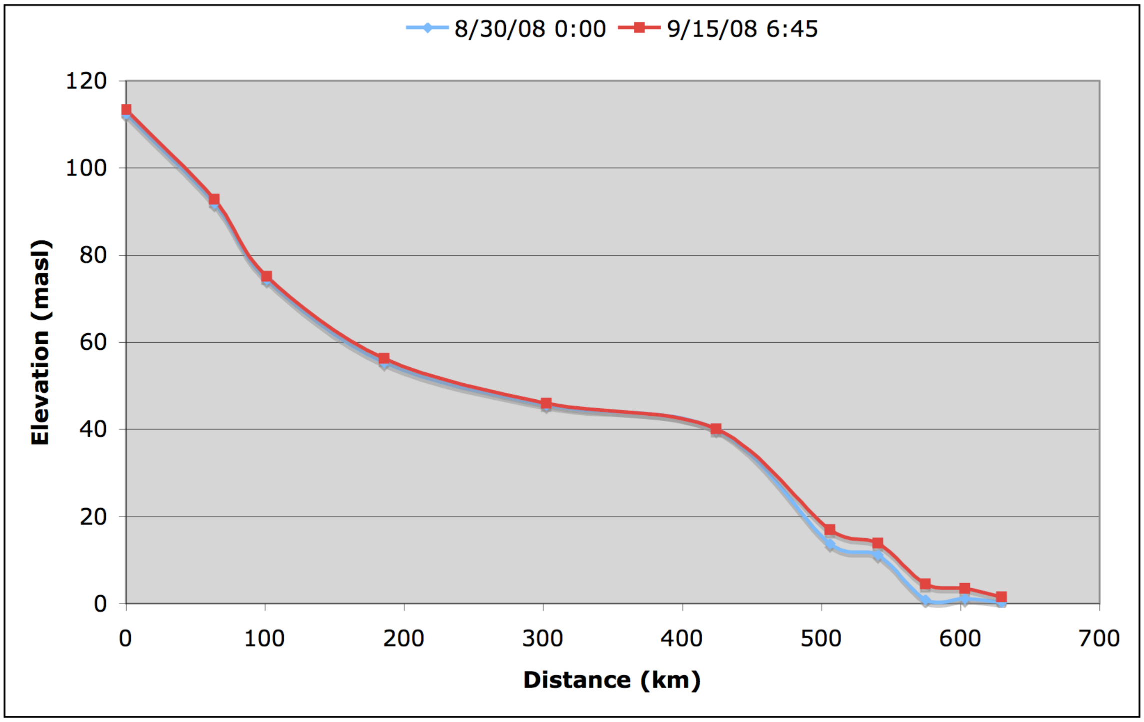
Second, the BCA identified 20 zones characterized by distinctive slopes (see chapter 3). Each station was thus assigned the slope associated with the zone it occurs within. Finally, the RiverTools software was used to determine the slope from the DEM data for a 10 to 20 km reach up- and downstream of each station, with the distance chosen depending on a visual assessment of consistent sinuosity.

Given the different techniques, quantitatively different results were to be expected. However, the three techniques gave different results with respect to increases or decreases in slope from one station to the next. Thus, water surface slopes were determined for two instantaneous periods during specific flow events. The first was determined to represent approximate steady-state flow between gaging stations, as indicated by a period not characterized by significant rising or falling stages at any station. The point chosen was 00:00 (midnight) the morning of 30 August, 2008. For comparison, an additional high (but not flood) flow was examined, for post-Tropical Storm Ike discharges. The specific time of comparison (06:45 on 15 September, 2008) corresponds with the hydrograph peak at Romayor.

The water surface elevation for each station was determined by adding stage (gage height) to the datum of the station, except for a few stations where water surface elevation above sea level is reported directly. The elevation difference between successive stations, divided by the channel distance between them, gives the water surface slope gradient. Results are shown in Figure 3.

The reach between the Riverside and Goodrich stations includes Lake Livingston. Lake backwater effects influence water levels at Riverside; thus the apparent slope gradient at Goodrich (~0.003) is too high. The channel gradient between Livingston Dam and the Goodrich station is considerably lower; about 0.0002. The channel at the Liberty, Moss Bluff, and Wallisville stations is below sea level; stages at these stations is thus influenced by wind- and tidally-driven water level fluctuations in Trinity/Galveston Bay. Because of the long distances between stations ($\geq$ 29 km), and variations in water level slopes during and between flow events (Fig. 4), the slope gradients derived in this analysis include considerable uncertainty. However, similar values were obtained for the two sample times, and the qualitative pattern (pattern of downstream increases or decreases in slope between stations) is identical. Further, the qualitative pattern for the stations downstream of Trinity Dam is similar to that found in earlier studies (Fig. 4). Thus the water surface slope gradients for the 30 August steady-state flow were used for stream power calculations. "Export" stream power (see Phillips and Slattery, 2007) was calculated for each station, based on the slope from that station to the next station downstream. The mean gradient from Liberty to Wallisville was used (i.e., Moss Bluff was not used) to eliminate the negative slopes in the coastal backwater-influenced zone.

Cross-sectional stream power was computed for the median and flood threshold flows at each station (Table 3). This shows a general but irregular downstream increase in flood power associated with median flows, with a pronounced increase from Crockett downstream as compared to upstream stations. The large increase between Oakwood and Crockett is generally associated with steeper slopes in the lower sections—though note that slopes decrease considerably downstream of Romayor (Phillips and Slattery, 2007).



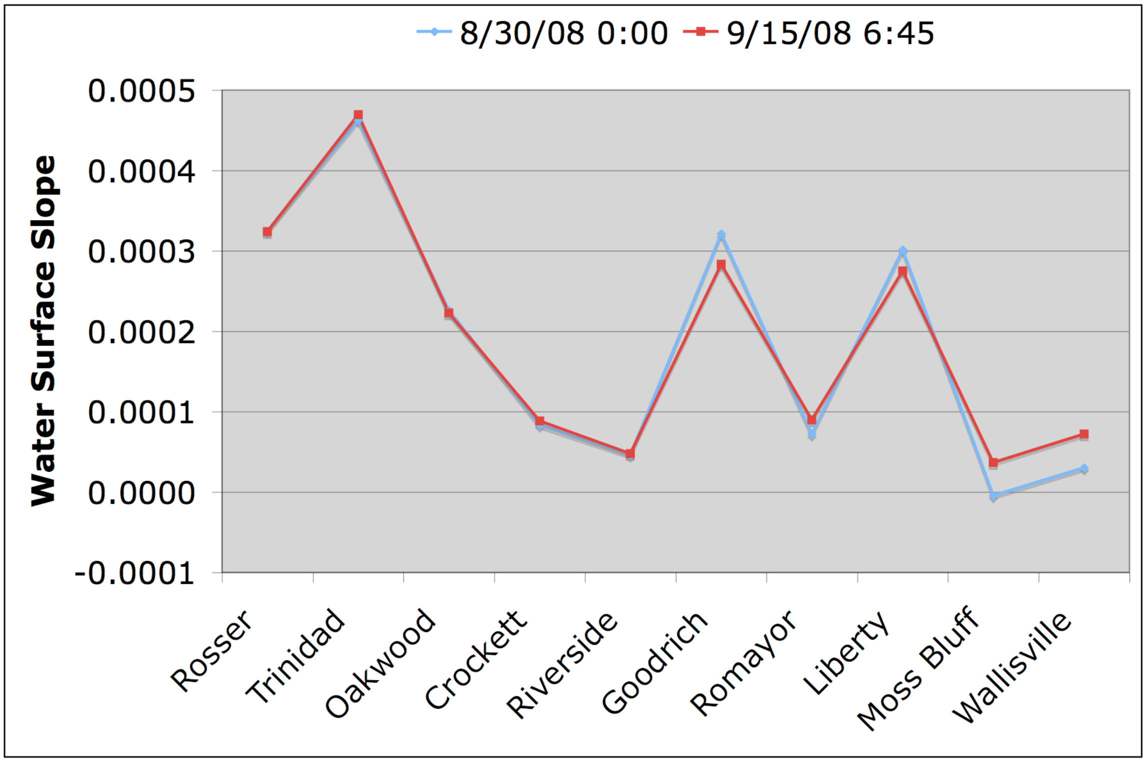


Figure 3. Water surface profiles from the gaging station on the Trinity River below Dallas to Wallisville (top), and slope gradients between stations (bottom). The gradient for each station represents slope from the station upstream.

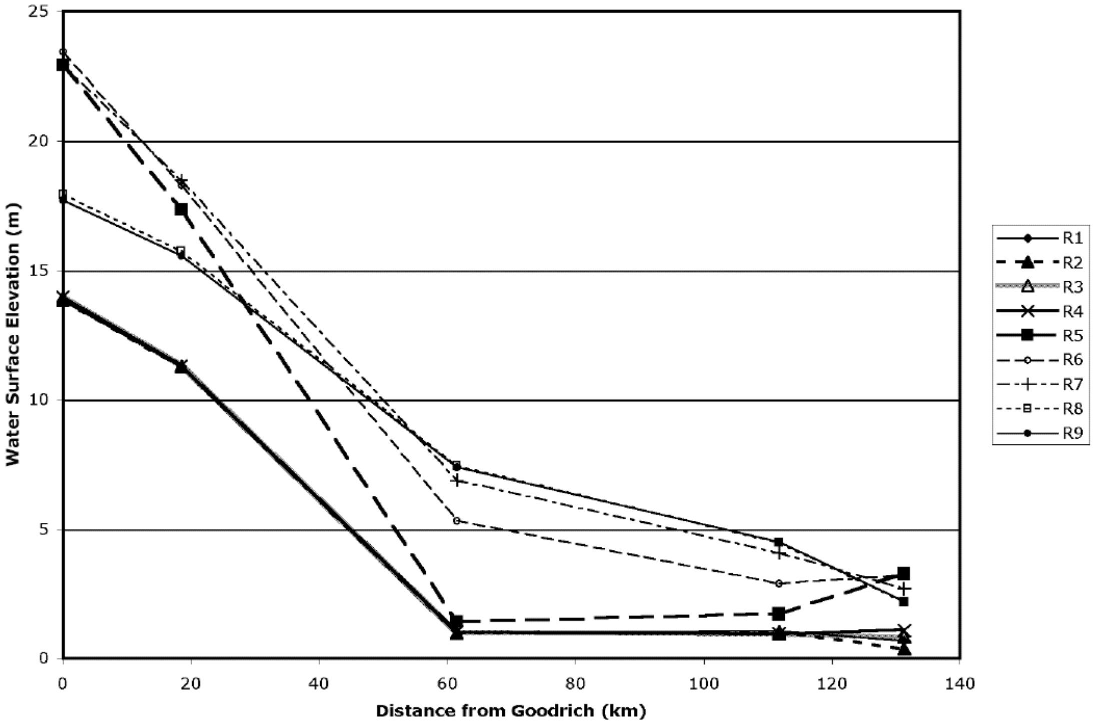


Figure 4. Water surface slopes associated with a multi-day flow event on the lower Trinity River in September, 2005 (see Phillips and Slattery, 2007 for details). R1-R9 represent key phases in the flow event. The data points are gaging stations from Goodrich to Wallisville.

Power associated with the channel-full threshold (Table 3) shows an even more irregular downstream trend. Note that in this case, while flood power at Crockett, Goodrich, and Romayor is significantly greater than for the Dallas, Rosser, Trinidad, and Oakwood stations, there is a significant drop between Romayor and Liberty. This is controlled by three factors—a decline in channel capacity, as illustrated by the increased frequency of overbank flows at Liberty; a topographically-controlled decrease in slope in the lowermost coastal plain section of the river; and backwater effects which further reduce energy grade slopes. The latter extend upstream of Liberty to the general area of Kenefick, Texas; and effects of Holocene sea level rise on valley morphology and sediment transport are evident as far upstream as a critical zone about 8 km below Romayor (Phillips et al., 2005; Phillips and Slattery, 2007.

Table 3. Cross-sectional stream power for selected flows (see Table 2) at Trinity River gaging stations (W/m).

Station	*Median (W/m)*	*Flood (W/m)*	*1-year*	*5-year*
Trinity R. below Dallas	71	926	2441	4650
Trinity R. nr Rosser	130	3373	5546	9621
Trinity R. @ Trinidad	84	1048	3219	4655
Trinity R. nr Oakwood	35	542	1547	2302
Trinity R. nr Crockett	28	529	754	1256
Trinity R. nr Goodrich	56	1224	1368	2032
Trinity R @ Romayor	227	7109	5725	7984
Trinity R @ Liberty		113	307	371

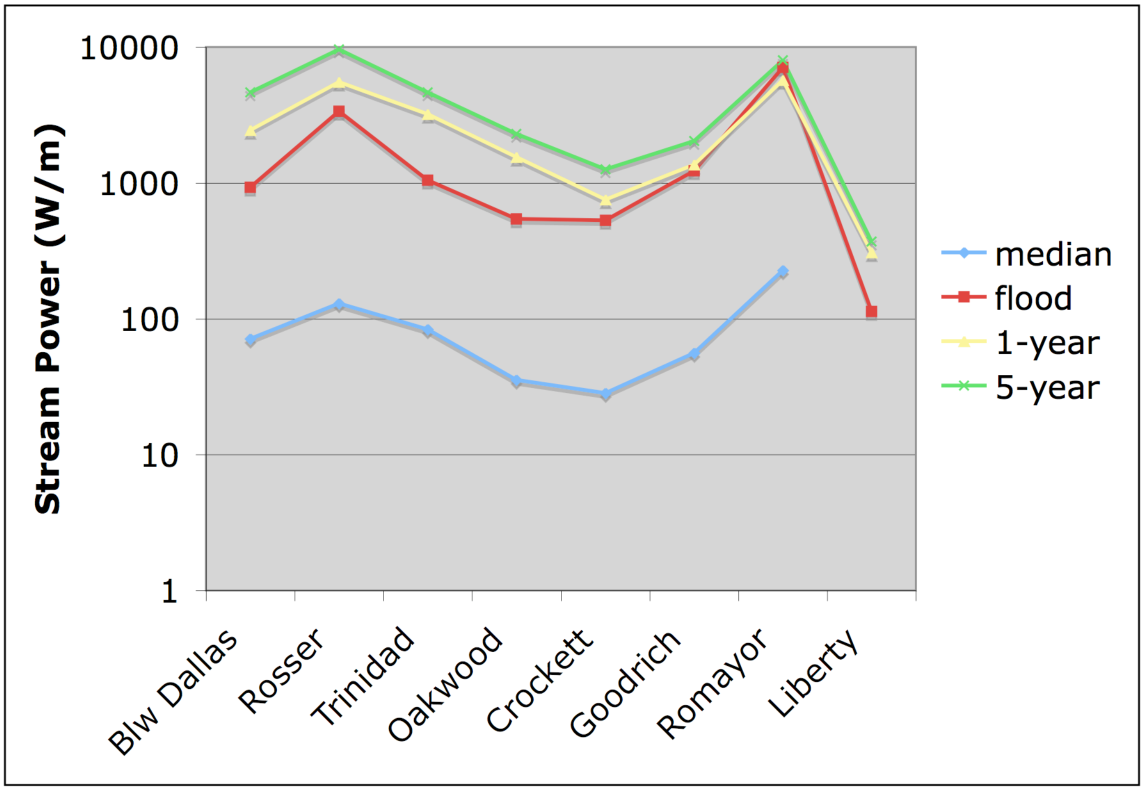


Figure 5. Downstream trend in cross-sectional stream power for several reference flows at Trinity River gaging stations.

The pattern of station-to-station increases and decreases in cross-sectional stream power is identical for all four reference flows (Figure 5). The stream power analysis confirms the reduced stream power and sediment transport bottleneck effects downstream of Romayor identified in previous work (Phillips et al., 2004; 2005; Phillips and Slattery, 2007). However, uncertainty with respect to slope gradients makes it difficult to draw firmer conclusions and points to a need for more detailed measurements of water surface or energy grade slopes at appropriate scales, which are generally distances of about 7 to 10 channel widths.

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. This resulted in the identification of 19 zones of distinctive channel slope over the 638 km of channel in the study area (Table 4). Two of these (Lake Livingston and the Trinity delta) are characterized by effects of impoundment and coastal/tidal influences, respectively. Mean slope gradients for the zones otherwise range from 0.0000001 to 0.0010044. The former (zone 11) is just upstream of Lake Livingston and influenced by the backwater effects of the lake. The steepest (zone 5) is controlled by a steep valley slope where the Trinity valley crosses one of the roughly coast-parallel cuestas which characterize the topography in the Eocene and Miocene sections.

Table 4. Zonation based on channel slope. DS lat and DS long, respectively, indicate the latitude and longitude of the downstream end of the reach. Distance and D-up, respectively, are distances in km downstream of the Elm Fork confluence or upstream of Trinity Bay.

Slope zones	DS lat	DS long	Distance	D - up	Slope
0	32.497	-96.501	0.00	638.21	0.0008615
1	32.467	-96.496	6.41	631.80	0.0032060
2	32.370	-96.448	24.76	613.45	0.0001618
3	32.202	-96.186	77.90	560.31	0.0001879
4	31.942	-96.017	143.38	494.83	0.0000518
5	31.873	-95.969	165.85	472.36	0.0010044
6	31.847	-95.992	170.28	467.93	0.0002277
7	31.703	-95.881	207.48	430.73	0.0000836
8	31.628	-95.718	246.82	391.39	0.0001825
9	31.377	-95.691	292.63	345.58	0.0000717
10	31.142	-95.756	336.66	301.55	0.0002142
11	30.808	-95.133	461.89	176.32	0.0000001
12	30.629	-95.012	490.26	147.95	Lake
13	30.577	-94.988	502.17	136.04	0.0003970
14	30.514	-94.862	523.79	114.42	0.0000449
15	30.450	-94.849	537.54	100.67	0.0002100
16	30.339	-94.795	559.20	79.01	0.0000992
17	30.251	-94.790	540.63	97.58	0.0001773
18	29.935	-94.780	600.21	38.00	0.0000587
19	29.755	-94.695	638.21	0.00	delta

Sinuosity

Sinuosity zones were determined using a combination of visual assessments of channel planform from aerial imagery and iterative (i.e., trial-and-error) sinuosity measurements using RiverTools. Fourteen sinuosity zones were identified (Table 5). All sinuosity values were >1.5, and four zones had values >2.

Table 5. Zonation based on sinuosity.

Sinuosity zone	DS lat	DS long	Distance	D-up	Sinuosity
0	32.497	-96.501	0.00	638.21	1.519
1	32.352	-96.449	27.48	610.73	2.096
2	32.256	-96.286	56.74	581.47	1.829
3	32.209	-96.197	76.38	561.83	1.960
4	31.991	-96.056	125.67	512.54	1.488
5	31.873	-95.969	165.85	472.36	2.292
6	31.789	-95.983	178.44	459.77	1.530
7	31.738	-95.870	201.61	436.60	1.890
8	31.393	-95.701	290.04	348.17	2.167
9	31.163	-95.728	332.38	305.83	1.756
10	31.017	-95.658	372.81	265.40	2.342
11	30.860	-95.398	424.39	213.82	1.638
12	30.629	-95.012	490.26	147.95	Lake
13	30.541	-94.830	519.08	119.13	1.577
14	29.755	-94.695	638.21	0.00	1.900

Valley Width

Valley width zones were delineated based on GIS measurements, resulting in 13 zones. Valley geometry varies in irregularity, and local expansions or constrictions of less than about 5 km in length were not considered to be separate zones. Thus the zones are characterized in Table 6 by minimum, maximum and mean widths, and the ratio of maximum to minimum as a coarse index of variability.

Valley widths are generally wider (10 to 15 km) downstream of Lake Livingston, with mean widths of zones upstream of the lake ranging from <4 to >9 km. Variability is highest (max-min ratios >3) where geologic controls create locally wider and narrower segments. All of the latter occur upstream of Lake Livingston.

Table 6. Zonation based on valley width. Columns min, max, and mean are minimum, maximum, and average valley widths (km); while ratio is max/min.

Valley width	lat	long	distance		min	max	ratio	mean
0	32.497	-96.501	0.00	638.21				
1	32.317	-96.360	39.10	599.11	5.25	8.50	1.62	7.50
2	32.098	-96.118	107.47	530.74	2.00	7.25	3.63	5.39
3	31.862	-95.980	168.06	470.15	5.25	9.00	1.71	7.64
4	31.628	-95.718	207.40	430.81	2.00	9.50	4.75	5.14
5	31.427	-95.712	286.62	351.59	3.75	14.00	3.73	9.41
6	31.163	-95.728	332.38	305.83	5.00	10.25	2.05	7.79
7	30.927	-95.640	385.57	252.64	5.00	8.00	1.60	6.83
8	30.860	-95.398	424.39	213.82	4.50	7.50	1.67	5.88
9	30.808	-95.133	461.89	176.32	1.75	5.50	3.14	3.75
10	30.629	-95.012	490.26	147.95	Lake			
11	30.422	-94.845	505.83	132.38	7.25	15.50	2.14	11.29
12	29.817	-94.737	628.75	9.46	6.00	14.50	2.42	10.06
13	29.755	-94.695	638.21	0.00	14.00	16.50	1.18	15.00

Valley Confinement

The 16 valley confinement zones are shown in Table 7. Because the Trinity River is a meandering, laterally migrating river with valleys mostly >5 km wide through most of the study area, the majority of zones are partly confined or unconfined. However, four confined reaches occur. These are relatively short (<16 km), while the other valley confinement zones are up to 119 km in length.

Table 7. Zonation based on valley confinement (C = confined; PC = partly confined; UC = unconfined). These categories are based on the proportion of the channel in direct contact (<100 m) with the valley wall (C: >90%; PC: 10 to 90%; UC: <10%).

Zone	DS lat	DS long	Distance	D-up	Category
0	32.497	-96.501	0.00	638.21	
1	32.470	-96.501	5.70	632.51	PC
2	32.317	-96.360	39.10	599.11	UC
3	32.233	-96.222	69.47	568.74	PC
4	32.202	-96.186	77.90	560.31	C
5	31.873	-95.969	165.85	472.36	PC
6	31.781	-95.954	182.53	455.68	C
7	31.640	-95.795	186.80	451.41	UC
8	31.628	-95.718	207.40	430.81	PC
9	31.499	-95.743	270.41	367.80	UC
10	31.427	-95.712	286.62	351.59	C
11	31.163	-95.728	332.38	305.83	UC
12	30.940	-95.450	406.87	231.34	PC
13	30.894	-95.313	421.40	216.81	C
14	30.629	-95.012	490.26	147.95	Lake
15	30.541	-94.830	519.08	119.13	PC
16	29.755	-94.695	638.21	0.00	UC

Geology

Zones 1-6 in Table 8 are characterized by late Cretaceous to Miocene formations, while zones 7-9 are Pleistocene to recent. The Eocene and Miocene areas in particular (zones 2-6) are characterized by complex local patterns and numerous formations. Several tectonic faults pass through the study area, and one major tectonic feature—the Elkhart Graben—characterizes zone 4.

Table 8. Zonation based on dominant geology bounding the river valley.

Geology	DS lat	DS long	Distance	D-up	
0	32.497	-96.501	0.00	638.21	Cretaceous
1	32.261	-96.285	56.74	581.47	Paleocene
2	32.156	-96.150	95.25	542.96	Eocene
3	31.781	-95.954	182.53	455.68	Eocene
4	31.628	-95.718	221.87	416.34	Elkhart Graben, Eocene
5	30.860	-95.398	424.39	213.82	Eocene
6	30.629	-95.012	490.26	147.95	Miocene
7	30.514	-94.862	523.79	114.42	Lissie, Willis
8	29.935	-94.780	600.21	38.00	Beaumont
9	29.755	-94.695	638.21	0.00	Delta (Holocene)

Channel-Floodplain Connectivity

The degree of hydraulic connectivity between the channel and floodplain was assessed based on the frequency of overbank flow at gaging stations as described in chapter 2, on descriptions of flooding impacts at various stages for the gage sites in the AHPS database (AHPS, 2008), presence of anabranches, paleochannels and high-flow channels, apparent backwater effects at tributary mouths, and presence of oxbows and other floodplain depressions near the active channel.

The 17 reaches in Table 9 range from very high connectivity in the delta and downstream of the critical zone below Romayor to very low in zones 3, 5, and 9. The very highly connected reaches are characterized by frequent overbank flows, numerous floodplain depressions, and a variety of subchannels resulting from Quaternary avulsions (see Phillips, 2008). The very low reaches are associated with an incised river channel with high banks and an absence of paleochannels or depressions on the floodplain.

Table 9. Zonation based on channel-floodplain connectivity. Shown are the connectivity category and the type of relevant features found on the floodplain (Anb = active or high flow [hiflow] anabranch; Plc = paleochannel (abandoned river channel); Oxb = oxbow lake or swamp; dep = major floodplain depression; BW crks = creeks with obvious backwater effects; dist = distributary channels)

	DS lat	DS long	Distance	D-up	VC	Features
0	32.497	-96.501	0.00	638.21		
1	32.389	-96.439	20.25	617.96	Low	
2	32.317	-96.360	39.10	599.11	High	Anb,Plc,Oxb
3	32.251	-96.241	65.70	572.51	Very low	
4	32.171	-96.173	90.94	547.27	Medium	Plc, Oxb
5	32.153	-96.137	96.81	541.40	Very low	
6	32.032	-96.062	119.66	518.55	Medium	Plc, Oxb
7	31.870	-95.989	162.11	476.10	Low	
8	31.862	-95.980	168.06	470.15	Medium	Plc, Oxb
9	31.781	-95.954	182.53	455.68	Very low	
10	31.163	-95.728	332.38	305.83	Medium	Plc, Oxb
11	31.053	-95.632	364.37	273.84	Low	
12	30.860	-95.398	424.39	213.82	High	Plc, Oxb, dep, BW crks
13	30.894	-95.313	438.92	199.29	Very high	LL backwater
14	30.629	-95.012	490.26	147.95	Lake	
15	30.403	-94.824	509.50	128.71	Medium	Oxb, hiflow Anb, dep
16	29.935	-94.780	600.21	38.00	Very high	Plc, Oxb, dep, BW crks, hiflow Anb
17	29.755	-94.695	638.21	0.00	Very high	dist, tidal, Anb, dep, BW crks

BOUNDARY COINCIDENCE

Many of the boundaries identified in Tables 4-9 are coincident, due to covariation and interrelationships between the criteria, and to responses to common controls and influences. Figure 6 identifies 18 locations where two or more criteria boundary are co-located. Given the inherent transitional nature of some criteria, and imprecision associated with the resolution of GIS data, boundaries within 5 km of each other were considered to be coincident. Each of the locations identified in Figure 6 was examined in an effort to determine the geomorphic controls over these key transition points.

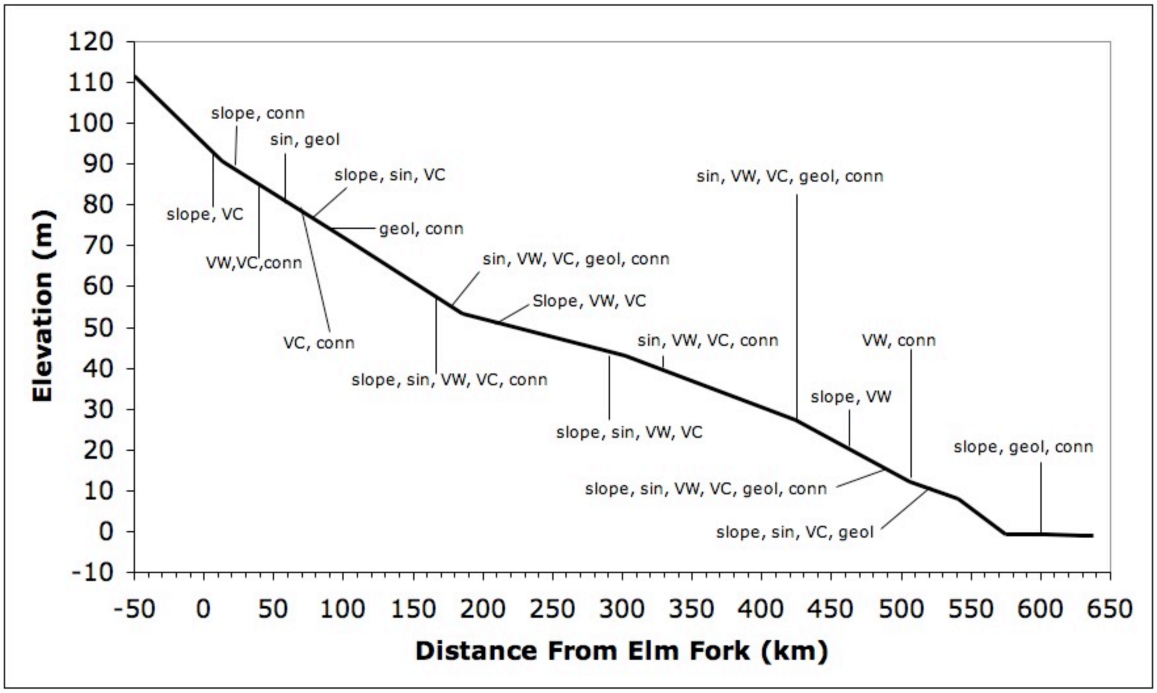


Figure 6. Coincident boundaries along the Trinity River study area for slope, sinuosity (sin), valley width (VW), valley confinement (VC), geology (geol), and channel-floodplain connectivity (conn). Profile is based on gaging station datum elevations, extended to Trinity Bay.

INTERPRETATIONS

Figure 7 assigns a number to each of the transition points shown, and Table 10 provides a brief interpretation of the underlying cause of the transition. The areas around sites 13-18 have been examined in the field in conjunction with previous work (Phillips, 2008; Phillips et al., 2004; 2005; Phillips and Musselman, 2003; Phillips and Slattery, 2007; 2008). Interpretation of points 1-12 relied on GIS data.

Local valley narrowing, associated with relatively narrow protrusions of uplands into the river valley, appear to be responsible for critical points 1 and 5, and valley constriction also plays a role at site 8. These topographic constraints locally influence slope, valley confinement, sinuosity, and channel-floodplain connectivity as well as valley width, and may result in downstream propagation of related changes. Sites 1 and 5 are not clearly related to mapped geologic boundaries, but rather with variations in valley-wall geometry. Point 8 is directly associated with a narrow outcrop of the Carrizo Sand formation, extending in a roughly NNE-SSW axis across the river valley.

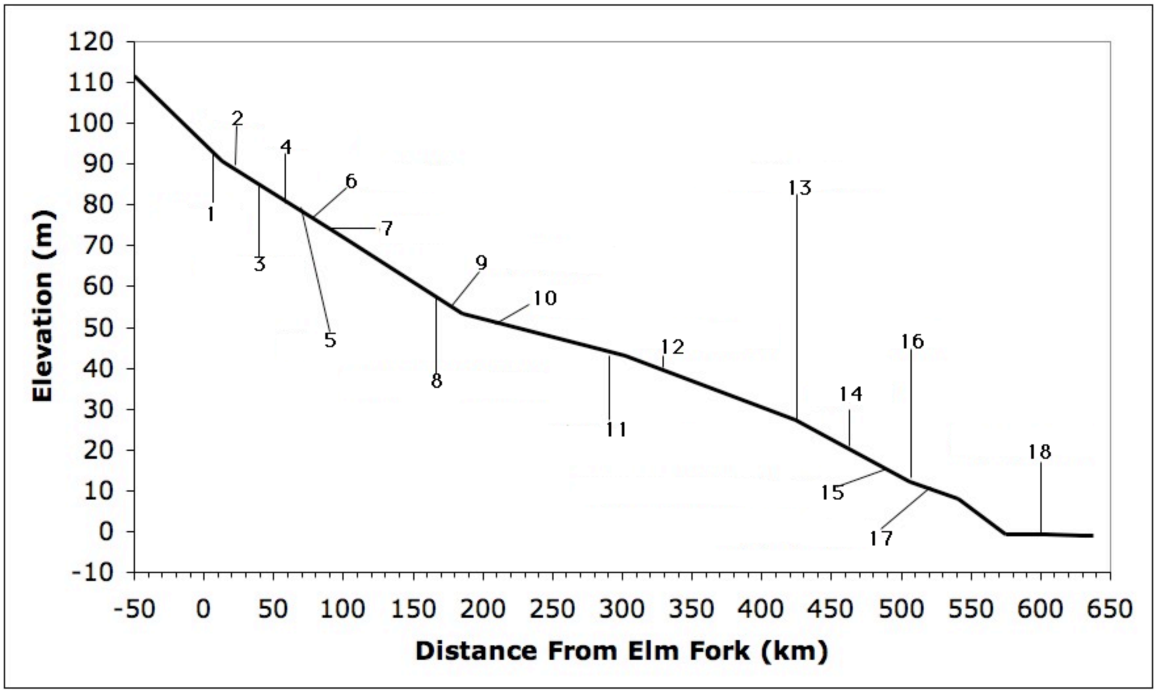


Figure 7. Key linking the transition points in Figure 6 to Table 10.

Table 10. Summary of geomorphic controls over critical transition points (locations as shown in Figures 6,7).

1. Local valley narrowing
2. Anabranching reach
3. Valley constriction; downstream end of avulsion
4. Boundary between Paleocene and Eocene formations
5. Local valley narrowing
6. Major tributary confluence; upstream end of avulsion
7. Downstream end of avulsion
8. Valley constriction associated with Carrizo Sand formation
9. Elkhart Graben
10. Elkhart Graben
11. Valley constriction
12. Upstream end of avulsion; structural lineament?
13. Lake Livingston backwater
14. Valley widening
15. Valley constriction; Miocene/Quaternary geologic boundary; Livingston Dam
16. High flow floodplain distributary; floodplain depression; critical zone
17. High flow floodplain distributary; floodplain depression; critical zone
18. Head of delta

General valley narrowing or widening (as opposed to local constrictions) are found at transition points 3, 11, 14, and 15. Beyond the valley width criterion, valley extent is inversely related to valley confinement, and potentially directly related to sinuosity and connectivity (due to increased space for meander belts, abandoned channels, and floodplain depressions). Sinuosity may in turn be related to slope, and valley width changes may be associated with geologic controls.

Five transition points (4, 8, 9, 10, 15) are collocated with mapped geologic features. Site 4 is at the boundary between Paleocene and Eocene formations, and 8, as mentioned above, is related to the Carrizo Sand. A major tectonic feature, the Elkhart Graben, influences points 9 and 10, and 15 is at the approximate boundary between Quaternary and Tertiary formations.

Avulsions

The Trinity, like other rivers in the region, has experienced a number of Quaternary channel shifts or avulsions (Aslan and Blum, 1999; Phillips, 2008). Abandoned channels may persist as semi-active high flow channels or floodplain depressions, or as active anabranches or distributaries. Because slope advantages play an important role in avulsions, they may also be associated with slope changes. The GIS data was examined to identify abandoned river channels, and their intersections with the modern channel were mapped.

Seven avulsions were identified in the valley downstream of Lake Livingston, as reported in Phillips (2008). Upstream of the lake, it could not be confirmed whether the mapped features represent separate avulsions, or multiple intersections of the modern channel with a single paleochannel, though almost certainly multiple avulsions have occurred between Elm Fork and Lake Livingston. As many as seven avulsions were identified, each represented by an upstream and downstream point of intersection with the modern channel/floodplain.

Avulsions play a key role in the formation and maintenance of multiple distributary channels in the Trinity delta area (transition point 18), and an active anabranch persists in the upper portion of the study area (2). Points 3, 6, 7, and 12 correspond with the upstream or downstream intersections with Trinity paleochannels, and flow diversion through a paleochannel between Goodrich and Romayor (see Phillips and Slattery, 2007) plays a key role in transition points 16 and 17.

Lake Livingston

Backwater effects of Lake Livingston become an important influence on valley and channel geomorphology at point 13. This is in part because the upstream limit of backwater effects of the impoundment are related to geologic, valley width, and valley confinement controls. The backwater effects themselves reduce slope, and increase channel-floodplain connectivity.

Similarly, the transition point 15 at Livingston Dam reflects both the geologic and topographic effects which made this a suitable site for dam construction (geology, valley width) and the geomorphic effects of the dam itself.

Other Factors

Transition points 16 and 17, upstream and downstream of Romayor, represent an interrelated pair of transition zones associated with natural flow diversion through a paleochannel and Pleistocene floodplain depression, and the upstream limit of the geomorphic effects of Holocene sea level rise. These are discussed in detail by Phillips and Slattery (2007, 2008).

The Elkhart Graben includes a complex set of faults which has likely directly influenced the river (see Schumm, 2000 for a general discussion of tectonic effects on alluvial rivers and a case study for the Neches River, Texas). Indirect effects apparently persist in the form of secondary controls of Quaternary alluvial terrace remnants. The Elkhart Graben influences transition points 9 and 10 near Palestine, influencing slope, valley width and confinement, geologic outcrops, and channel/floodplain connectivity. Figures 8 and 9 show a Quaternary terrace remnant, an avulsion site and paleochannel, and variations in the Eocene geologic outcrops. A more detailed assessment of geomorphic history of this area would require field work.

Point 12, near Crockett, is associated with an area of channel change, associated with a large depression associated with the Pleistocene "Deweyville" flow regime (see chapter 1). A tributary from the northeast occupies an oversized and usually straight channel/valley (Figure 10), and the meander belt of the Trinity River downstream is aligned in the same general direction. The topography and channel geometry in the vicinity suggest the possibility of a structural lineament, perhaps associated with a fault. However, there are no mapped faults or structural features in the GAT maps, and fieldwork would be required to further investigate this possibility.

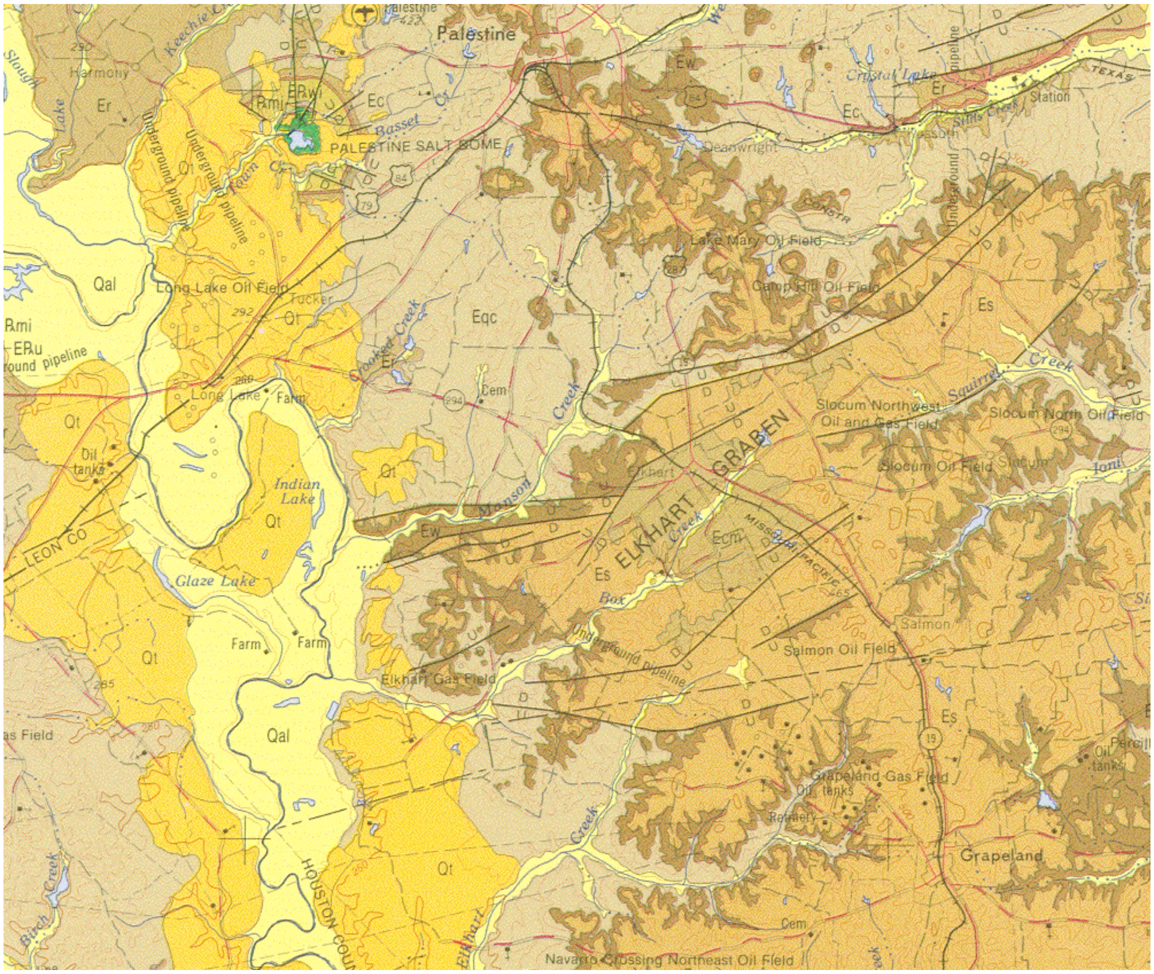


Figure 8. Section of the 1:250,000 scale Palestine Sheet of the Geologic Atlas of Texas, in the vicinity of transition points 9 and 10 near Palestine and Grapeland. Qal is Quaternary alluvium and Qt Quaternary (Pleistocene) alluvial terraces. Other mapped formations are Eocene.

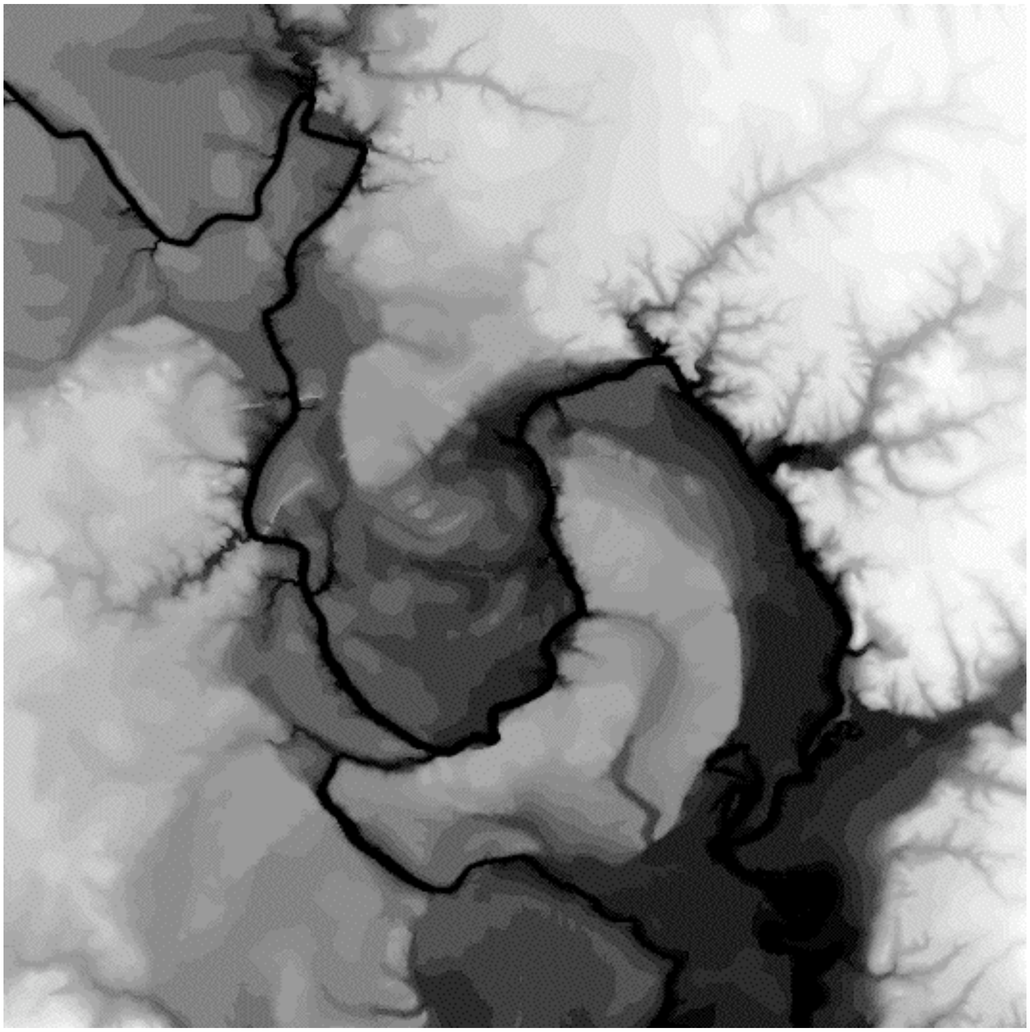


Figure 9. Topography in the vicinity of transition points 9 and 10 near Palestine and Grapeland. Density map based on DEM data.

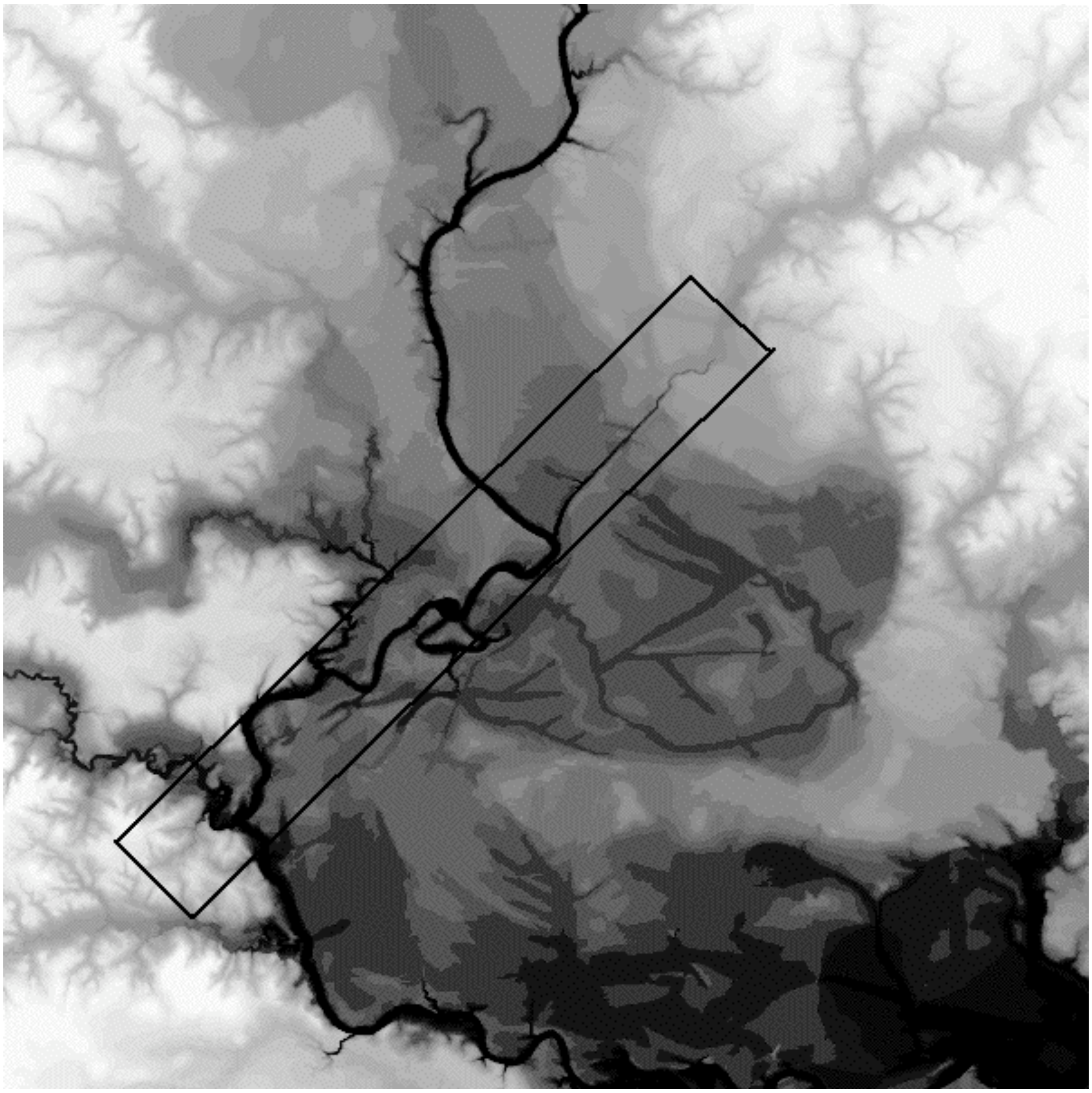


Figure 10. Topography in the vicinity of transition point 12, west of Crockett. The box shows the channel alignments suggesting a possible structural lineament.

Potential Future Changes

Geologic controls are important in determining the nature and location of critical transition points 1, 3, 4, 5, 8, 9, 10, 11, 12, 14, and 15. Over time scales relevant to water resource management these are mainly fixed and unlikely to experience changes sufficient to influence river hydrology and morphology. However, two of these (3, 12) are also associated with avulsions and potentially subject to change in that regard.

Avulsions are associated with channel and valley aggradation, and sensitive to subtleties of floodplain and valley topography and to effects of individual floods. Thus land use, climate, water withdrawal, sea level rise, subsidence, and other changes which may influence sediment supply and flow regimes are likely to influence these reaches. Influences of climate, land use, and water withdrawal/release would apply to all the critical transition points influenced by avulsions (numbers 2, 3, 6, 7, 12, 16, 17, 18). Effects of sea level rise may apply to those downstream of Livingston Dam, and subsidence to the Trinity River delta area. While the precise location and timing of avulsions is unpredictable, channel changes in avulsion-prone sections are likely to occur over decadal to century time scales.

Ongoing—and potentially accelerating—Holocene sea level rise will influence critical transition zones 16-18, generally causing an upstream migration of these points. The upstream migration is likely to be slow and gradual, except when critical thresholds are encountered, generally associated with "climbing" an alluvial terrace surface (see Rodriguez et al., 2005). Livingston Dam will serve as a buffer against the effects of sea level change upstream of the dam.

Any future changes in Lake Livingston, including increases or decreases in capacity, removal, or changes in operation rules, will influence critical points 13-15.

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 middle and lower Trinity 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; 2007).

ZONE DESCRIPTIONS

Below is a list of the major geomorphic zones of the Trinity River from the confluence with the Elm Fork near Dallas to Trinity Bay at Anahuac. The major distinguishing characteristics of the river style are given, along with any particularly significant demarcations between zones.

1. Elm Fork Confluence Zone

The confluence of the Elm Fork and the main stem of the Trinity River increases the flow of the latter (based on median flows) by about 34 percent. This reach is characterized by the steepest channel slopes in the study area and a sinuosity >2, and is partly confined. The channel-floodplain connectivity is low.

2. Avulsed Unconfined Alluvial Valley

Zone 2 features a meandering to strongly meandering channel in an unconfined valley. An abandoned channel course is present, but connectivity is low, as the paleochannel is not in proximity to the active channel.

3. Anastamosed

Two meandering to strongly meandering anabranches are present in this unconfined reach, creating high channel-floodplain connectivity.

4. Avulsed Unconfined Alluvial Valley 2

An unconfined meandering channel intersects an anbandoned channel course. This, along with several oxbows, creates high channel-floodplain connectivity.

5. Alluvial Valley Transitional

The transitional nomenclature indicates that within this ~ 27 km reach are found a succession of transitions in channel slope, sinuosity, valley confinement, and connectivity. However, these boundaries doe not coincide, and define relatively short subreaches. The location of zone 5 is apparently geologically controlled, comprising most of the Paleocene formations separating the upstream Cretaceous from the downstream Eocene geology.

6. Avulsed Alluvial Valley Transitional

The transitional nomenclature indicates that within this ~ 30 km reach are found a succession of transitions in sinuosity, valley width, valley confinement, and channel-floodplain connectivity, the latter ranging from very low to medium. However, these boundaries doe not coincide, and define relatively short subreaches. Disconnected fragments of one or more abandoned channel courses account for the variations in connectivity. This reach also marks the upstream limit of significant morphological influence of Pleistocene paleomeanders and floodplain depressions.

7. Low Gradient Alluvial Valley

Extremely low channel slopes dominate this partly confined reach, where sinuosity ranges from low to >2. As in zone 6, disconnected fragments of one or more abandoned channel courses account for variations in connectivity (very low to medium).

8. Steep High Sinuosity Alluvial Valley

This strongly meandering reach has relatively steep channel slopes and is partly confined with medium channel-floodplain connectivity. Transition from zone 8 to 9 coincides with a valley constriction and the geologic boundary between the Carrizo Sand and the Recklaw Formation (both Eocene).

9. Avulsed Unconfined Alluvial Valley 3

Zone 9 differs from the other avulsed unconfined alluvial valley zones (2, 4) in geologic setting (Eocene vs. Cretaceous), and in having greater variability than the upstream reaches in channel slope, valley confinement, connectivity, and (especially) valley width. Influenced by a large paleomeander and Quaternary terrace remnant.

10. Low Gradient, High Sinuosity Alluvial Valley 2

Similar to zone 7, but with more variation in sinuosity and valley width, and less in channel-floodplain connectivity. Influenced by large paleomeander and Quaternary terrace remnant.

11. Elkhart Graben Avulsed Valley

This reach is tectonically influenced by the Elkhart Graben, and exhibits evidence of a complex history of geologically recent channel shifts. A wide, unconfined valley with a strongly meandering channel occur here.

12. Low Gradient Wide Alluvial Valley

Extremely low channel slopes, sinuosity >2, and a wide valley dominate this reach, which is mostly unconfined but does include a constricted subreach.

13. Unconfined Alluvial Valley

Zone 13 is characterized by relatively consistent channel slope (low), sinuosity (1.5 to 2), confinement (unconfined), and channel-floodplain connectivity (medium). Transition from zone 13 to 14 coincides with geologic boundary between the Manning and Yegua formations (both Eocene).

14. High Sinuosity Avulsed Alluvial Valley

A strongly meandering channel in a partly-confined valley with low channel-floodplain connectivity characterizes this reach. While fragments of former river channels exist, they are not generally well connected to the active channel.

15. Fluvial Lake Backwater

This extremely low slope zone includes confined, partly confined and unconfined subreaches, and meandering to strongly meandering planform. The high channel-floodplain connectivity is largely attributable to backwater effects due to a raised baselevel from Lake Livingston. Backwater flooding of tributaries and some channel infill from bank progradation are evident. The river takes a major turn to the east in this zone, associated with faulting which diverted flow in the geologic past.

16. Fluvial Backwater—Lake Delta—Upper Lake

The key characteristic of this reach is a transition from backwater-influenced but dominantly fluvial hydrology (see zone 15) through the deltaic area in upper lake Livingston to the uppermost lake. The relative importance of downstream flow vs. backwater effects varies with river discharge (and, to a much lesser extent, lake levels). Reaches 16 and 17 are also associated with Miocene geology, in contrast with Eocene formations upstream, and Quaternary downstream of Livingston Dam.

17. Lake Livingston

Zone 17 begins in the area always dominated by lake (rather than inflow) hydrology, and ends at Livingston Dam. Reaches 16 and 17 are associated with Miocene geology, in contrast with Eocene formations upstream, and Quaternary downstream of Livingston Dam.

18. Livingston Dam Scour

"Hungry water" scour from Livingston dam releases has scoured the channel, which has only a thin, mobile alluvial cover over compact pre-Holocene clays and/or bedrock.

Channel widening has occurred in recent decades, and sediment concentrations are lower than upstream of the dam or downstream of zone 19.

19. Livingston Dam Scour 2

Similar to above, but valley is bounded by the Beaumont formation vs. the Willis and Lissie in zone 18. Channel-floodplain connectivity is higher due to high-flow subchannels and backwater influences on tributaries. The downstream end of this reach corresponds with the upstream limit of influences of Holocene sea-level driven aggradation.

20. Lower Coastal Plain

This wide-valley, unconfined reach exhibits very high connectivity due to frequent overbank flow, numerous oxbows, sloughs and paleochannels, and backwater-influenced tributaries. Antecedent topography associated with late Pleistocene paleomeander scars and depressions exert import controls on valley morphology and flow regimes (especially at high flow). The upstream end of this reach corresponds with the upstream limit of influences of Holocene sea-level driven aggradation, and is a zone of extensive sediment storage and low sediment transport capacity.

21. Delta

The Holocene deltaic reach has a very wide valley and a distributary network including both consistently active and high-flow anabranches. Antecedent topography associated with late Pleistocene paleomeander scars and depressions exert import controls on valley morphology and flow regimes. Coastal (tidal and wind-driven) backwater effects, with occasional ponding and upstream flow, occur throughout. The lowermost portion of the reach includes tidal marshes.

ZONE LOCATIONS

The locations shown for each zone (Table 11) are for the downstream end of the reach, which corresponds with the upstream end of the following reach. Distances are channel distances measured from predominantly 2004-vintage photography from Google Earth. The upstream reference is the confluence of the main and Elm Forks of the Trinity River; the downstream reference is the Trinity River navigation channel at Anahuac Park. In addition to latitude/longitude coordinates (in decimal degrees) a general locational description relative to map landmarks is given. (US, DS = upstream, downstream; TX = Texas state highway; U.S. = U.S. highway)

Table 11. Zone Locations.

Zone	Dist Downstream	Dist Upstream	Length (km)	Latitude	Longitude	Description
0	0	638.21	0	32.497	-96.501	Elm Fork Confluence
1	6.41	631.80	6.4	32.467	-96.496	W of Rosser; US of TX 34
2	20.25	617.96	13.8	32.389	-96.439	S of Rosser, DS of TX 34
3	27.48	610.73	7.2	32.352	-96.449	E of Ennis, between TX 34 and 85
4	39.10	599.11	11.6	32.317	-96.360	TX 85
5	65.70	572.51	26.6	32.251	-96.241	SW of Tool, near Cedar Cr. Reservoir
6	95.25	542.96	29.6	32.156	-96.150	WNW of Trinidad, US of TX 31
7	143.38	494.83	48.1	31.942	-96.017	E of Richland Chambers Reservoir, DS of U.S. 287
8	165.85	472.36	22.5	31.873	-95.969	NW of Palestine; near Fairfield Lake
9	186.80	451.41	21.0	31.640	-95.795	WSW of Palestine, US of U.S. 84/79
10	207.48	430.73	20.7	31.703	-95.881	DS of U.S. 84/79 , SW of Palestine
11	246.82	391.39	39.3	31.628	-95.718	SW of Palestine, E of Elkhart
12	292.63	345.58	45.8	31.377	-95.691	WNW of Crockett, US of TX 7
13	332.38	305.83	39.8	31.163	-95.728	SW of Crockett, US of TX 21
14	364.37	273.84	32.0	31.053	-95.632	SSW of Crockett, DS of TX 21
15	424.39	213.82	60.0	30.860	-95.398	Loop 19 between Huntsville & Trinity
16	461.89	176.32	37.5	30.808	-95.133	U.S. 190 at Onalaska
17	490.26	147.95	28.4	30.629	-95.012	Livingston Dam
18	509.50	128.71	19.2	30.514	-94.862	ENE of Shepherd; US of Menard Cr.
19	523.79	114.42	14.3	30.403	-94.824	S of Romayor; DS of TX 787
20	600.21	38.00	76.4	29.935	-94.780	Picketts Bayou near Moss Bluff
21	638.21	0.00	38.0	29.755	-94.695	Trinity R. navigation channel, Anahuac

ZONE DESCRIPTIONS: DETAILS

Table 12 lists the general characteristics of the identified zones according to the following categories.

Slopes are characterized as follows, based on channel slopes computed from a 30-m resolution digital elevation model.

Backwater	influenced by coastal or lake backwater effects
Very low	<0.0002
Low	0.0002 – 0.0004
Moderate	0.0004 - 0.0006
Moderately steep	0.0006 – 0.0010
Steep	>0.001

Sinuosity categories are based on the following:

	Sinuosity value
Straight	<1.2
Low-sinuosity	1.2 – 1.5
Meandering	1.5 – 2.0
Strongly meandering	2.0 – 3.0
Tortuous	>3.0

Valley Width is based on the mean valley wall-to-wall width, and the ratio of maximum to minimum width.

Width	Mean width (km)
Narrow	<5
Medium	5 – 8
Wide	8 – 12
Very wide	>12

Variability	Max/Min width
Consistent	<2
Moderately variable	2 – 3
Variable	3 – 4
Highly variable	>4

Valley Confinement is abbreviated as UC (unconfined), PC (partly confined), and C (confined). Where more than one category is listed, distinct subreaches occur and the first-listed is the longest.

Connectivity denotes channel-floodplain connectivity and is a qualitative assessment (very low to very high) based on frequency of overbank flow; 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.

Geology indicates the dominant age of the formations bounding the river valley for the varieity of Cretaceous, Paleocene, Eocene, and Miocene formations. For the Quaternary the dominant formation is listed (Willis, Lissie, Beaumont). Note that most of the study area contains some Quaternary alluvial terrace remnants within the valley.

Table 12. Zone descriptions (continues on following page)

Zone	*Slope*	*Sinuosity*	*Valley width*	*Valley confinement*	*Connectivity*	*Geology*
1	steep	Strongly meandering	Medium, consistent	PC	low	Cretaceous
2	very low	Meandering to strongly meandering	Medium, consistent	UC	low	Cretaceous
3	Very low	Meandering to strongly meandering	Medium, consistent	UC	High (anabranching)	Cretaceous
4	Very low	Meandering	Medium, consistent	UC	High	Cretaceous
5	Very low	Meandering	Medium, variable	PC	Very low	Paleocene
6	Very low	Low sinuosity to meandering	Medium, variable	PC, C	Very low to medium	Eocene
7	Extremely low	Meandering	Medium, variable to consistent	PC	Very low to medium	Eocene
8	Steep	Strongly meandering	Medium, consistent	PC	medium	Eocene
9	Very low to low	Meandering	Medium, highly variable	UC, PC	Very low to medium	Eocene
10	Extremely low	Meandering to strongly meandering	Medium, highly variable	PC	Medium	Eocene
11	Low	Strongly meandering	Wide, variable	UC	Medium	Eocene, Elkhart Graben
12	Extremely low	Strongly meandering	Wide, variable	UC, C	Medium	Eocene
13	Low	Meandering	Medium, moderately variable	UC	Medium	Eocene
14	Low	Strongly meandering	Medium, consistent	PC	Low	Eocene
15	Extremely low	Strongly meandering to meandering	Medium, consistent	UC, PC, C	High	Eocene
	Continued	*on following*	*page*			

	Table 13	*continued*				
16	Extremely low to backwater	Meandering	Narrow, variable	C	Very high	Miocene
17	Backwater	Lake	Lake	Lake	Lake	Miocene
18	Low	Meandering	Wide, moderately variable	PC	Medium	Willis, Lissie
19	Very low	Meandering	Wide, moderately variable	PC, UC	Very high	Beaumont
20	Very low to low	Meandering	Wide, moderately variable	UC	Very high	Beaumont
21	Backwater	Meandering, anabranching distributary	Very wide, consistent	UC	Very high	Delta

POTENTIAL CHANGES

Possible changes in the nature and location of the river styles identified above are associated with urbanization, Lake Livingston, sea level rise, lateral migration, and avulsions.

Urbanization affects the flashiness of runoff hydrographs, and sediment delivery, particularly during construction phases. These effects are most pronounced in the Dallas area, and future changes will depend on urban sprawl in the southern portion of the Dallas metro area. These effects become progressively less evident downstream, and would primarily influence RS 1 and 2.

Ongoing growth the delta at the upstream end of Lake Livingston and continuing backwater effects will continue to result in upstream delta growth and some infilling in RS 15 and 16, but qualitative changes in the nature of these zones are unlikely. The same applies to the scour zones downstream of Livingston Dam (RS 18, 19). Incision to bedrock limits further downcutting in this area, and rates of widening appear to have slowed appreciably, though active lateral migration is likely (Phillips et al., 2005). Any future changes in Lake Livingston, including increases or decreases in capacity, removal, or changes in operation rules, will influence RS 15-19.

The middle and lower Trinity is an actively laterally migrating meandering river, characterized by growth and evolution of meander bends, and occasional cutoffs. This will continue along essentially all reaches except Lake Livingston (RS 17), though slower rates are likely in the lake backwater-influenced reaches (RS 15, 16), and in the most incised scour zone (RS 18). As a general principle, single meander loops tend to translate downstream, while compound loops with multiple lobes are more likely to migrate normal to the valley axis. Lateral migration is likely to be least in the single confined valley reach (RS 16), greatest in the unconfined zones (RS 2-4, 9, 11-13, 15, 19-21), and intermediate in the partially-confined styles (RS 1, 5-8, 10, 14, 18).

While channel changes are possible over decadal and longer time scale in the reaches subject to avulsions, the general character of these reaches is unlikely to be modified by any channels changes—though note that a successful avulsion makes a new avulsion in the same location unlikely for some time period. Channel changes are most likely in those reaches with high and very high channel-floodplain connectivity (RS 3, 4, 15, 19-21) and to a lesser extent in those with medium connectivity (RS 6-13, 18).

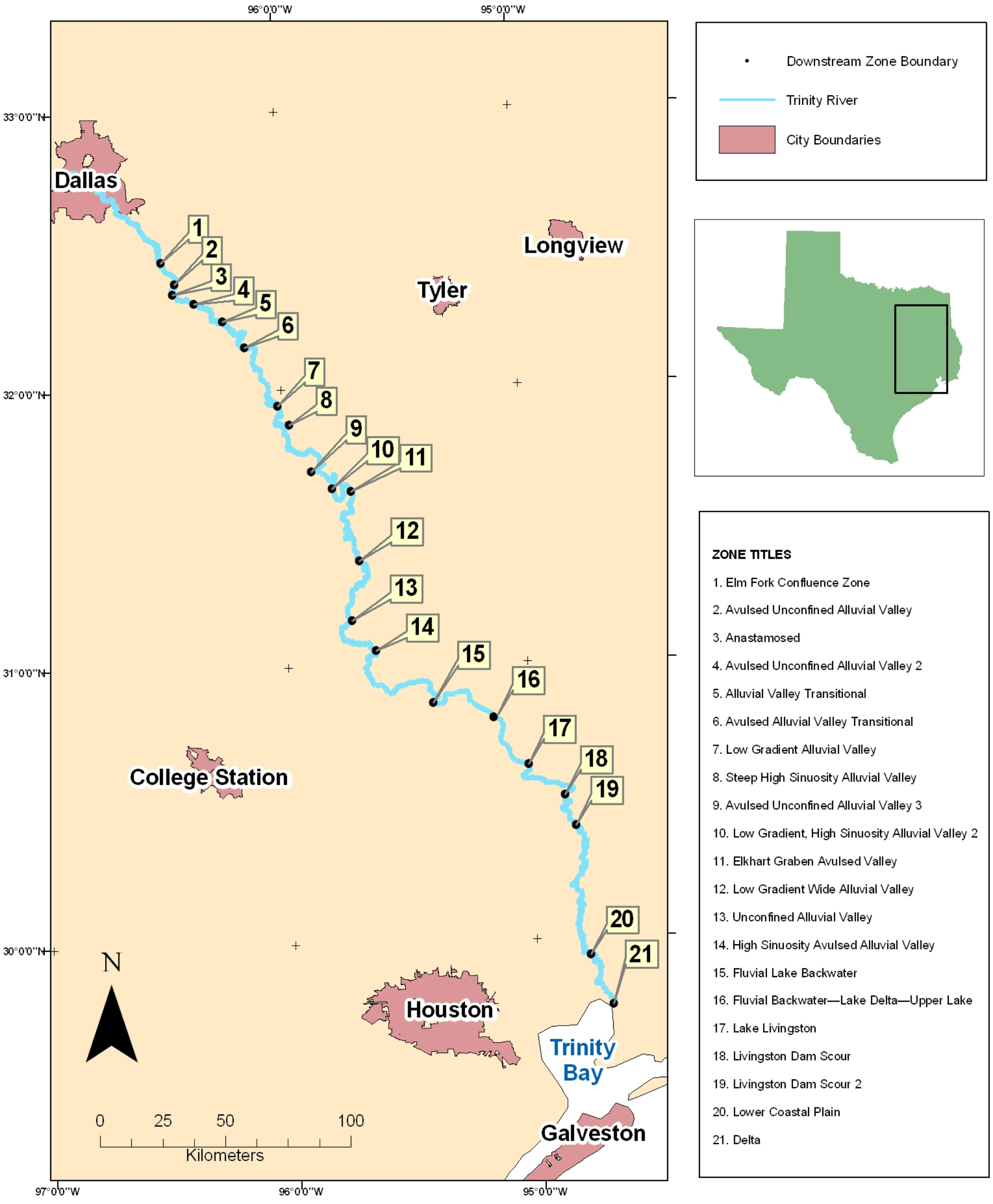
Sea level rise (combined with subsidence in the delta, RS 21) will continue to influence RS 20 and 21, and RS 20 may expand upstream somewhat at the expense of RS 19. Livingston Dam will serve as a buffer against the effects of sea level change upstream of the dam (RS 1-17).

MAPS

An overview map of the middle and lower Trinity River is provided, showing the downstream boundary of each zone, and the descriptive title as indicated above.

Following are maps of the individual zones. The background base map for these are digital orthophoto quarter quadranges (DOQQ's). The blue line is the Trinity River as indicated on the National Hydrography Database (NHD). Note that the river channel observed on the DOQQ's deviates from the NHD line in some cases.

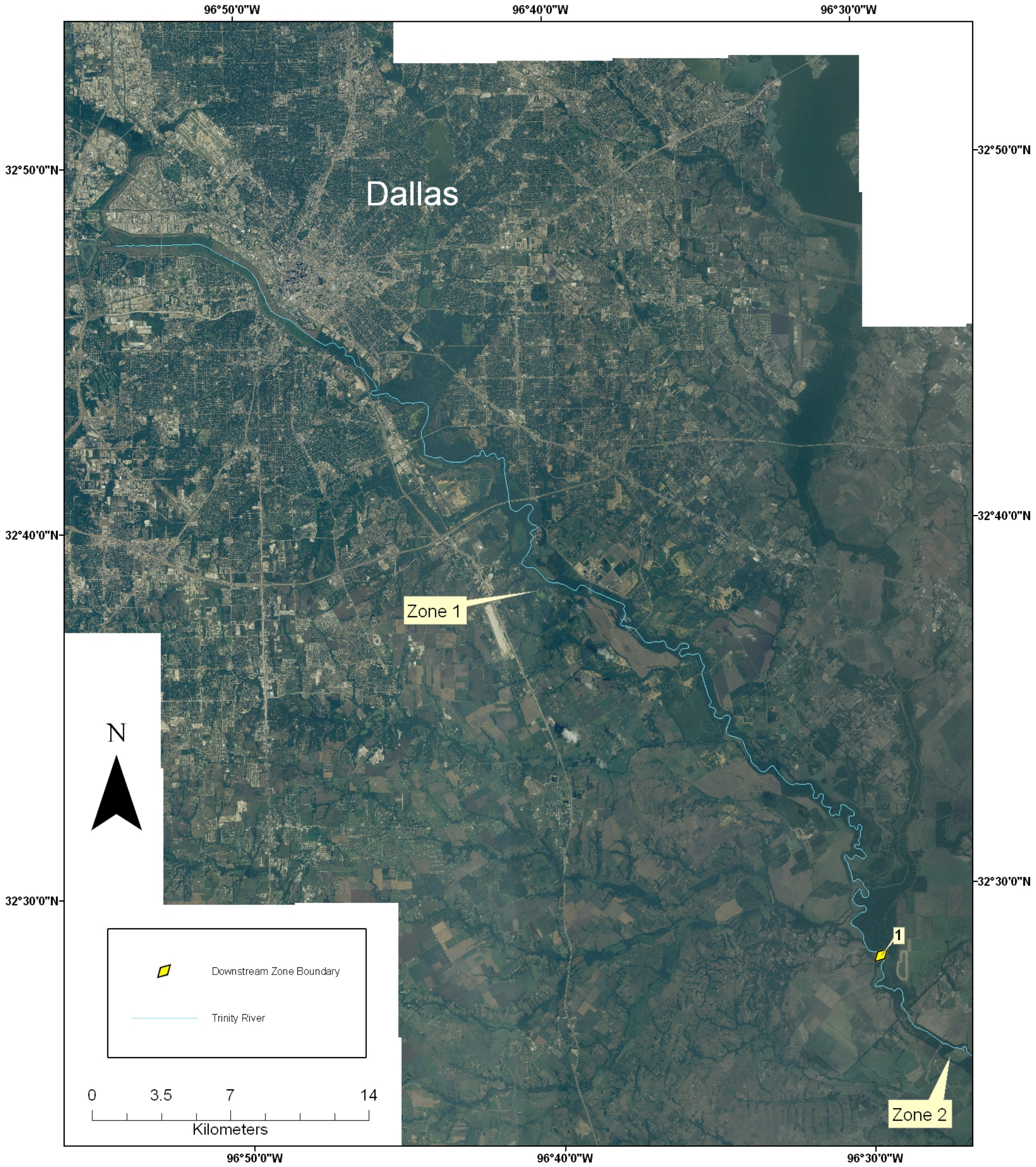
Trinity River - Downstream Zone Boundaries



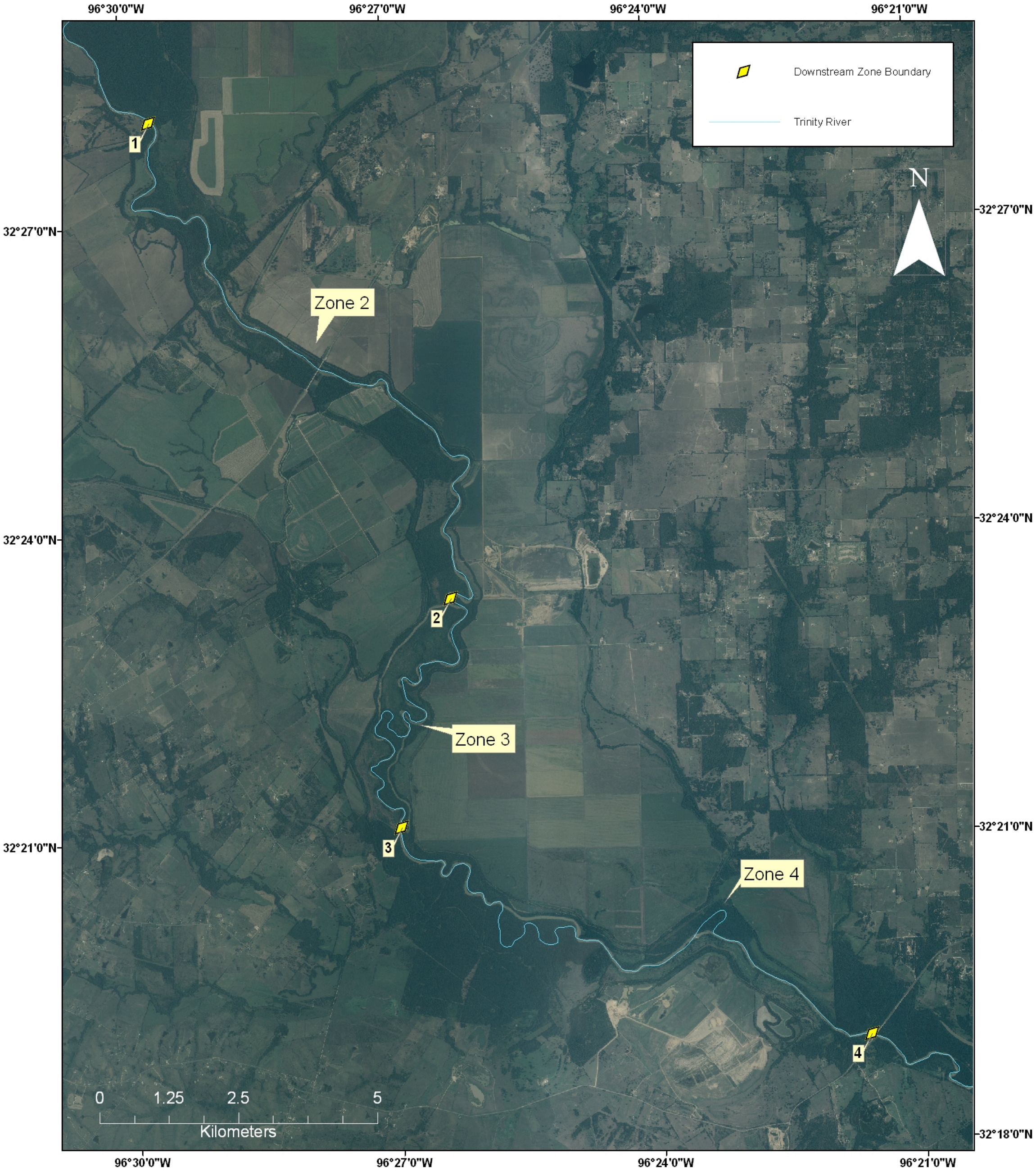
ZONE TITLES

1. Elm Fork Confluence Zone
2. Avulsed Unconfined Alluvial Valley
3. Anastamosed
4. Avulsed Unconfined Alluvial Valley 2
5. Alluvial Valley Transitional
6. Avulsed Alluvial Valley Transitional
7. Low Gradient Alluvial Valley
8. Steep High Sinuosity Alluvial Valley
9. Avulsed Unconfined Alluvial Valley 3
10. Low Gradient, High Sinuosity Alluvial Valley 2
11. Elkhart Graben Avulsed Valley
12. Low Gradient Wide Alluvial Valley
13. Unconfined Alluvial Valley
14. High Sinuosity Avulsed Alluvial Valley
15. Fluvial Lake Backwater
16. Fluvial Backwater—Lake Delta—Upper Lake
17. Lake Livingston
18. Livingston Dam Scour
19. Livingston Dam Scour 2
20. Lower Coastal Plain
21. Delta

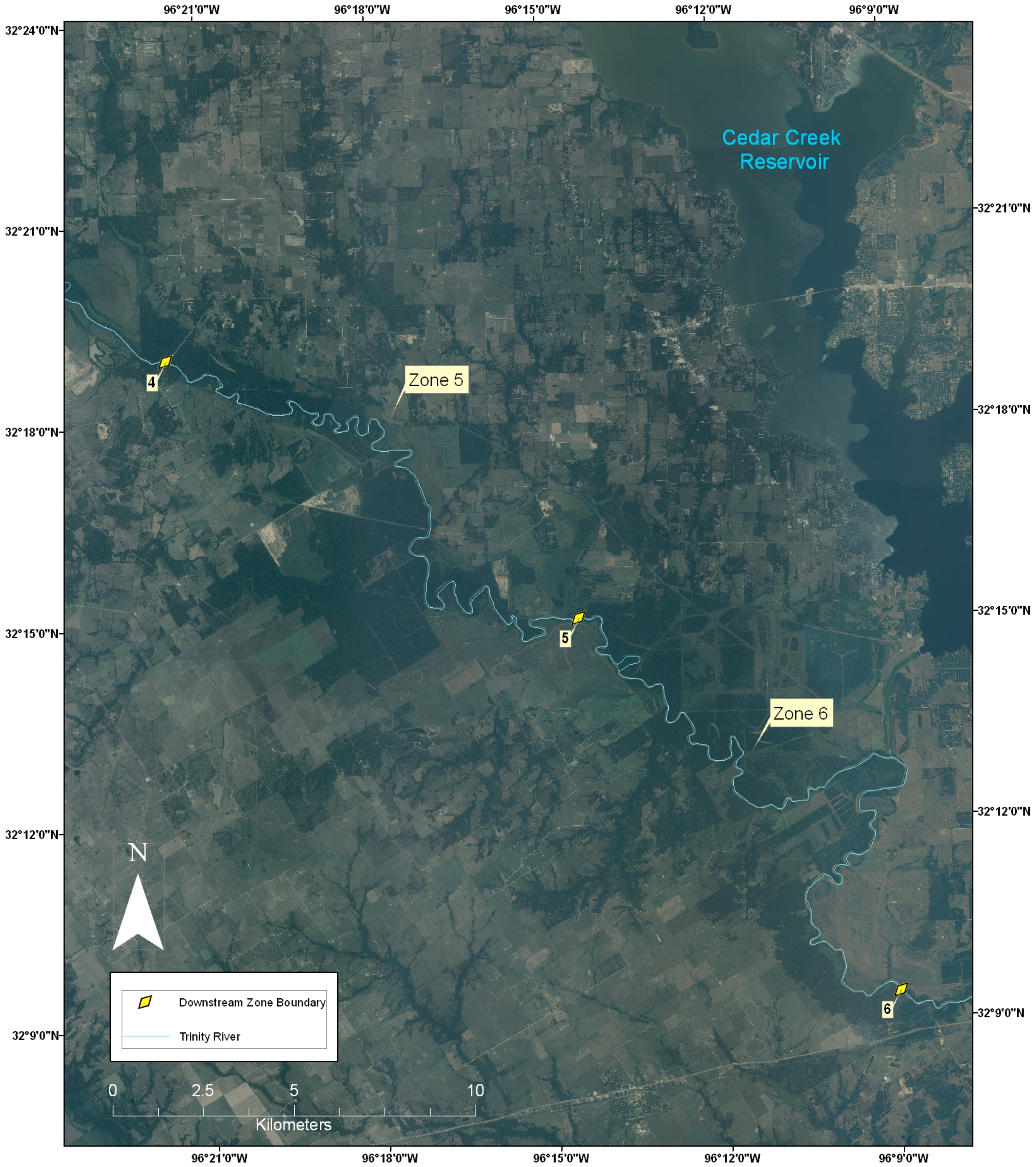
Trinity River - Zone 1



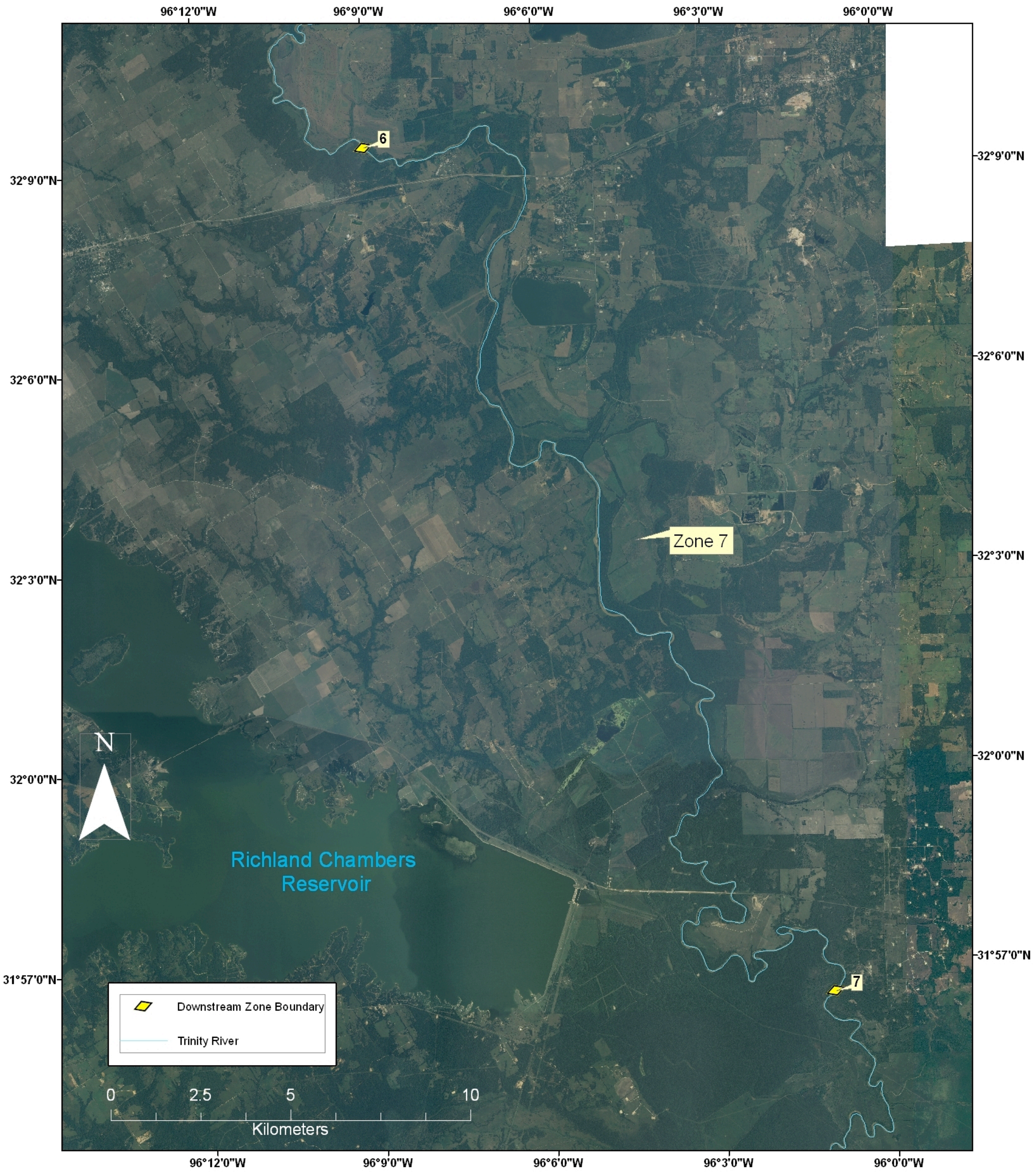
Trinity River - Zones 2 to 4



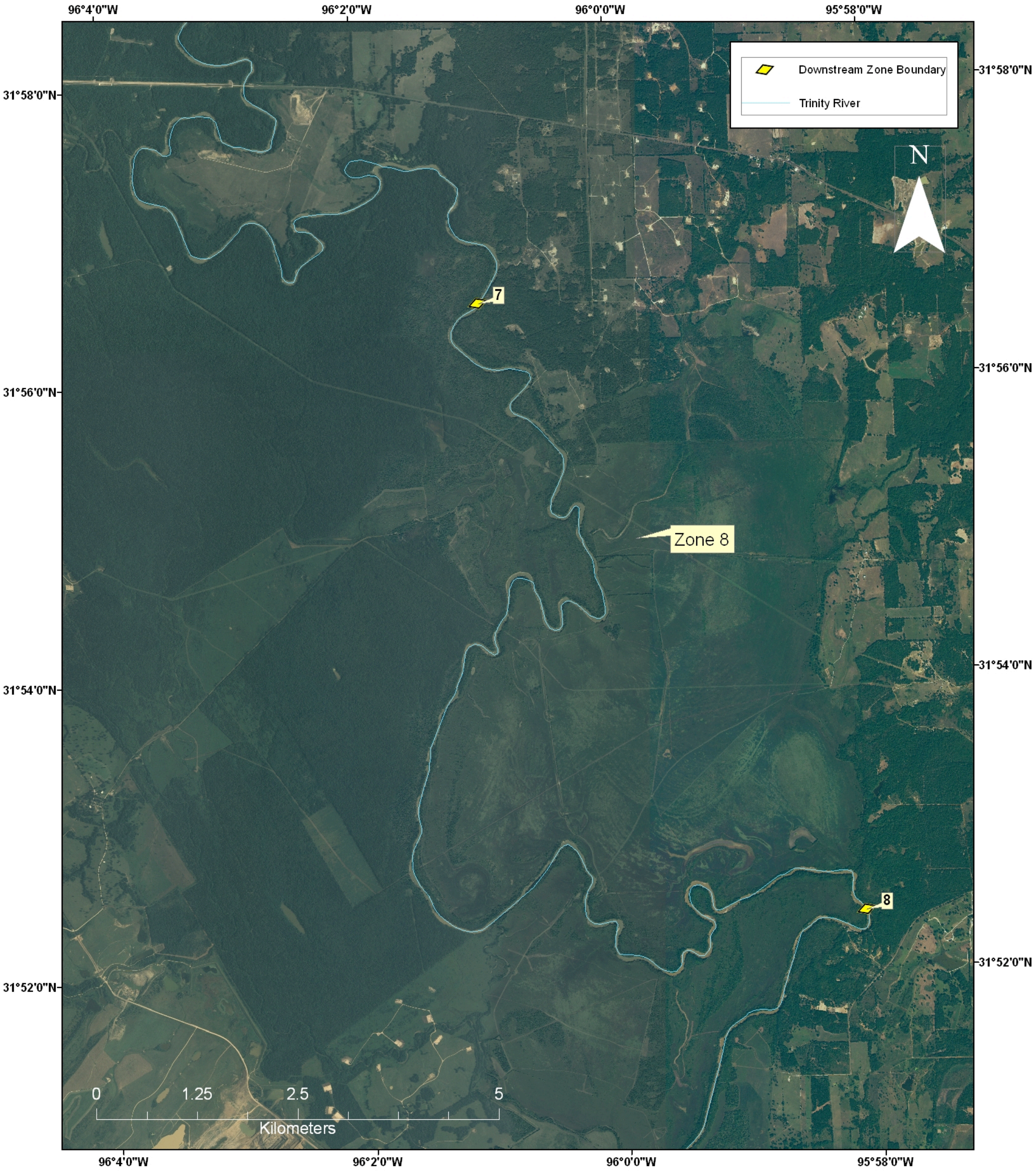
Trinity River - Zones 5 and 6



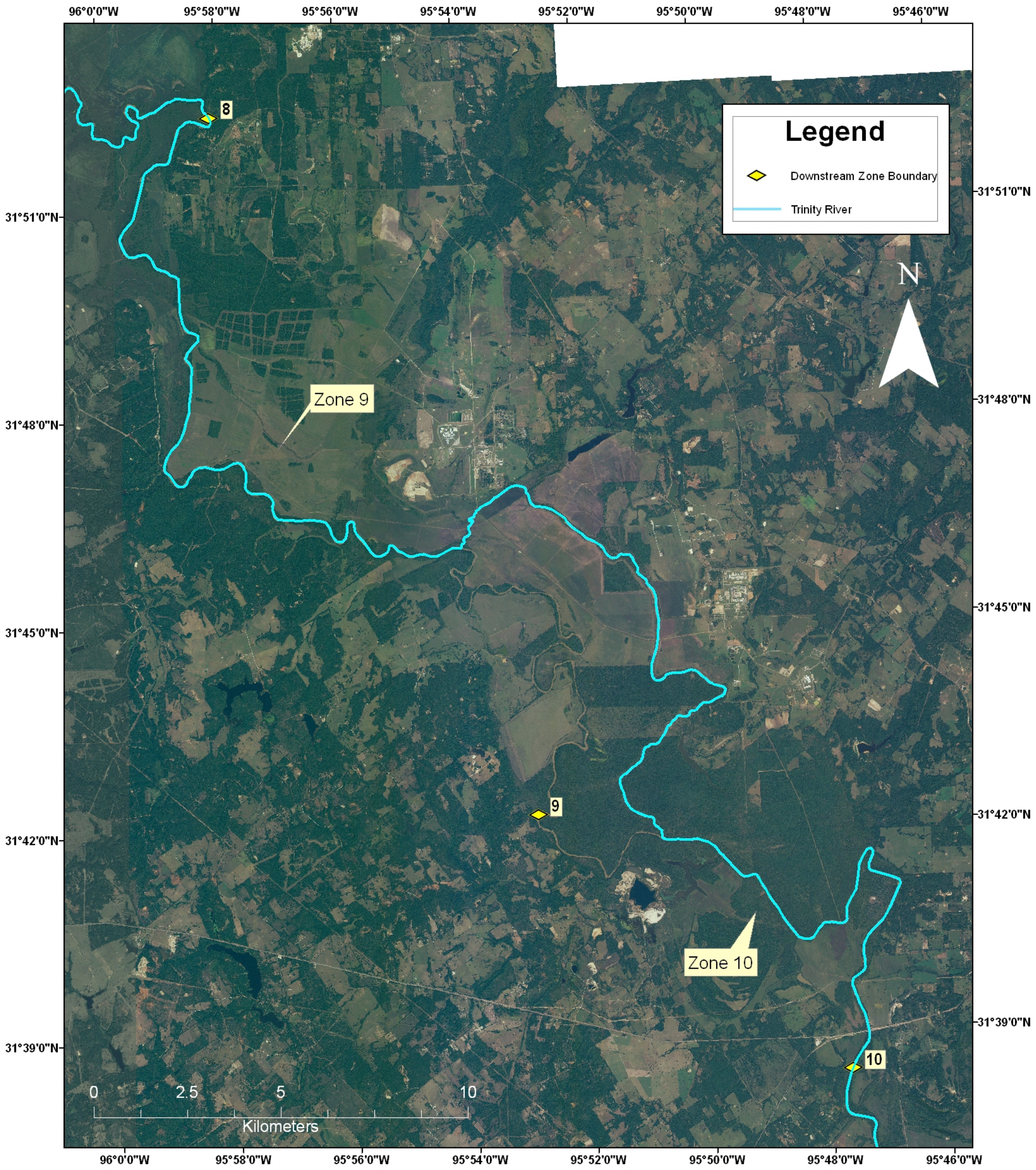
Trinity River - Zone 7



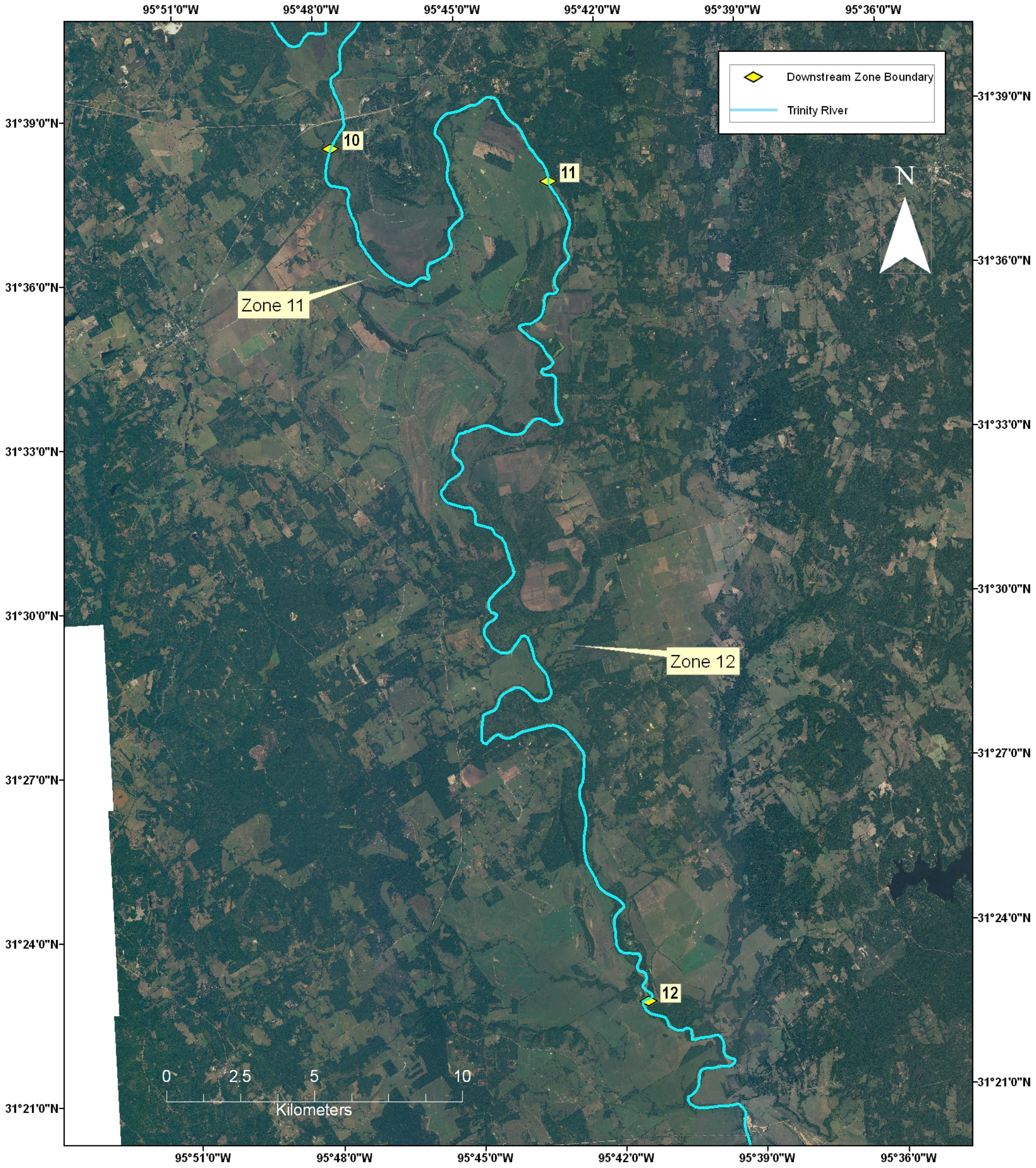
Trinity River - Zone 8



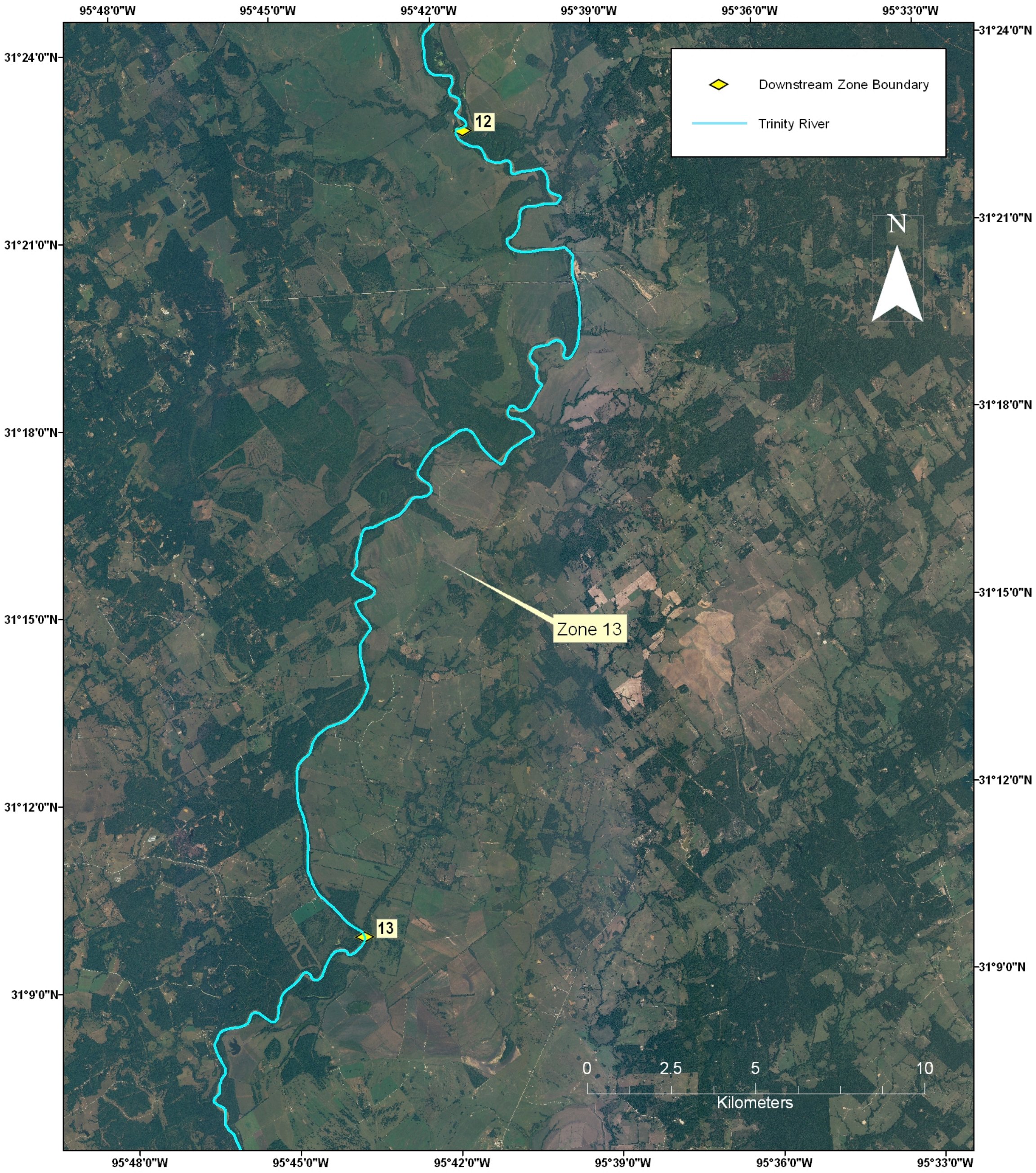
Trinity River - Zones 9 and 10



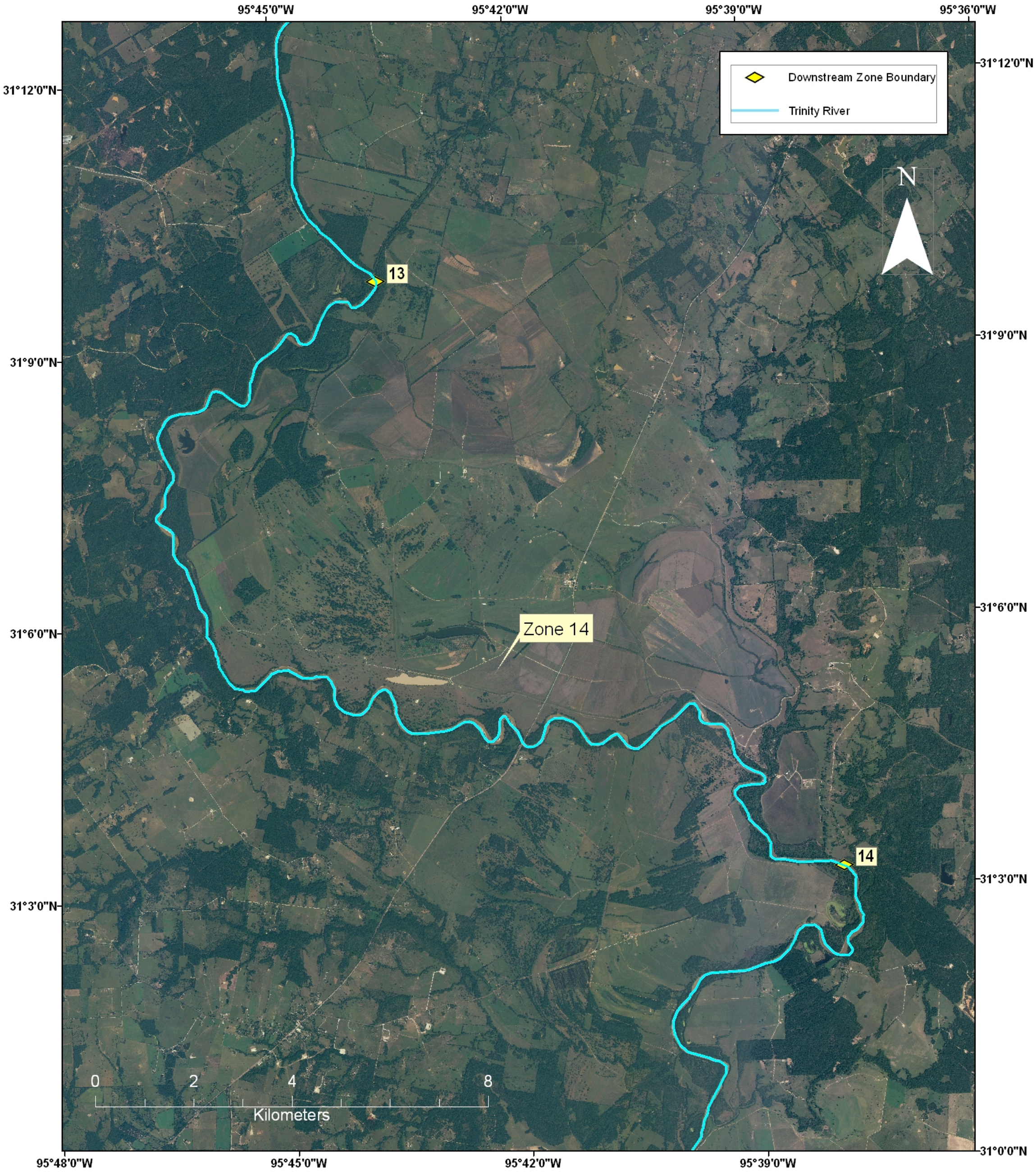
Trinity River - Zones 11 and 12



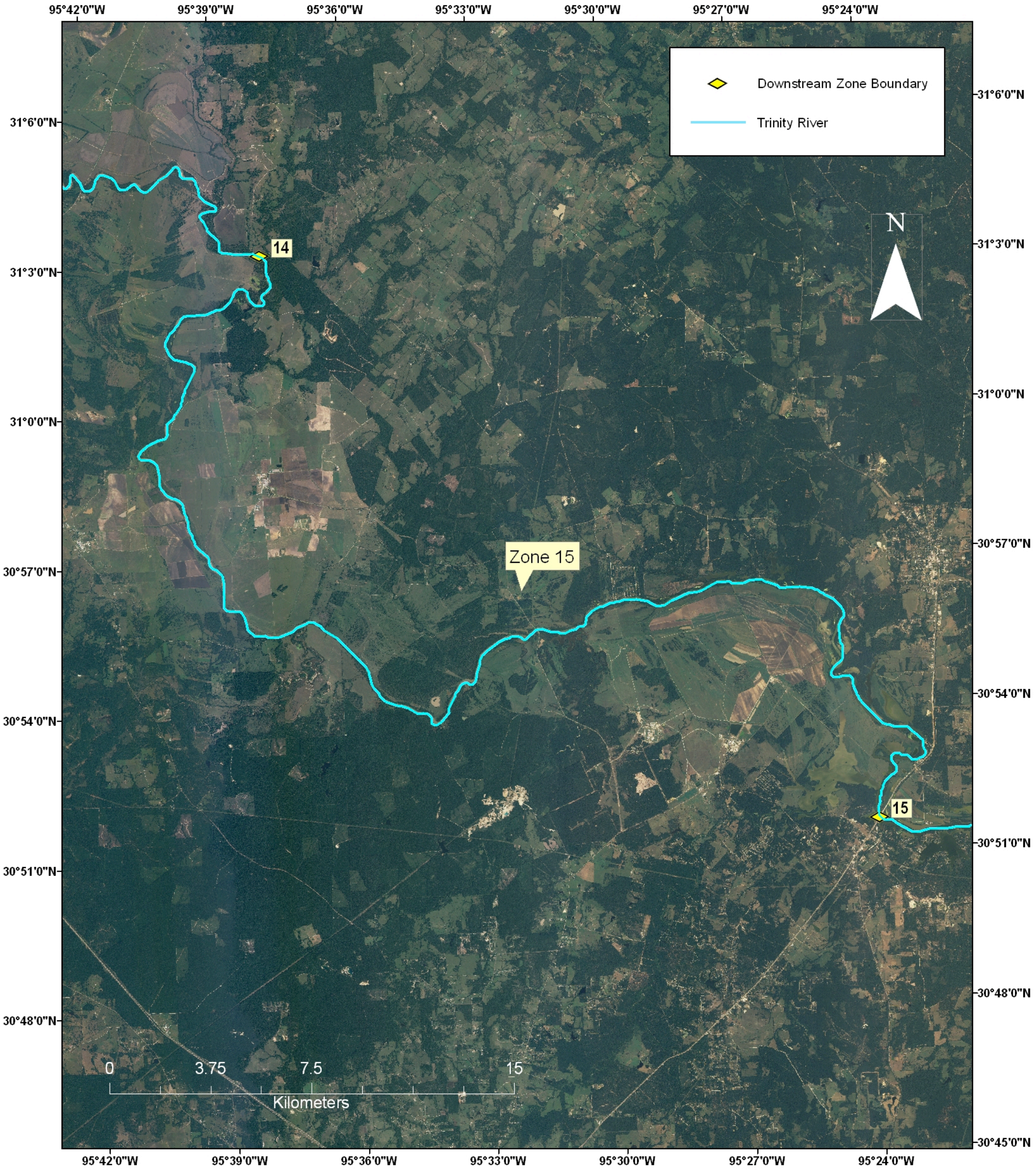
Trinity River - Zone 13



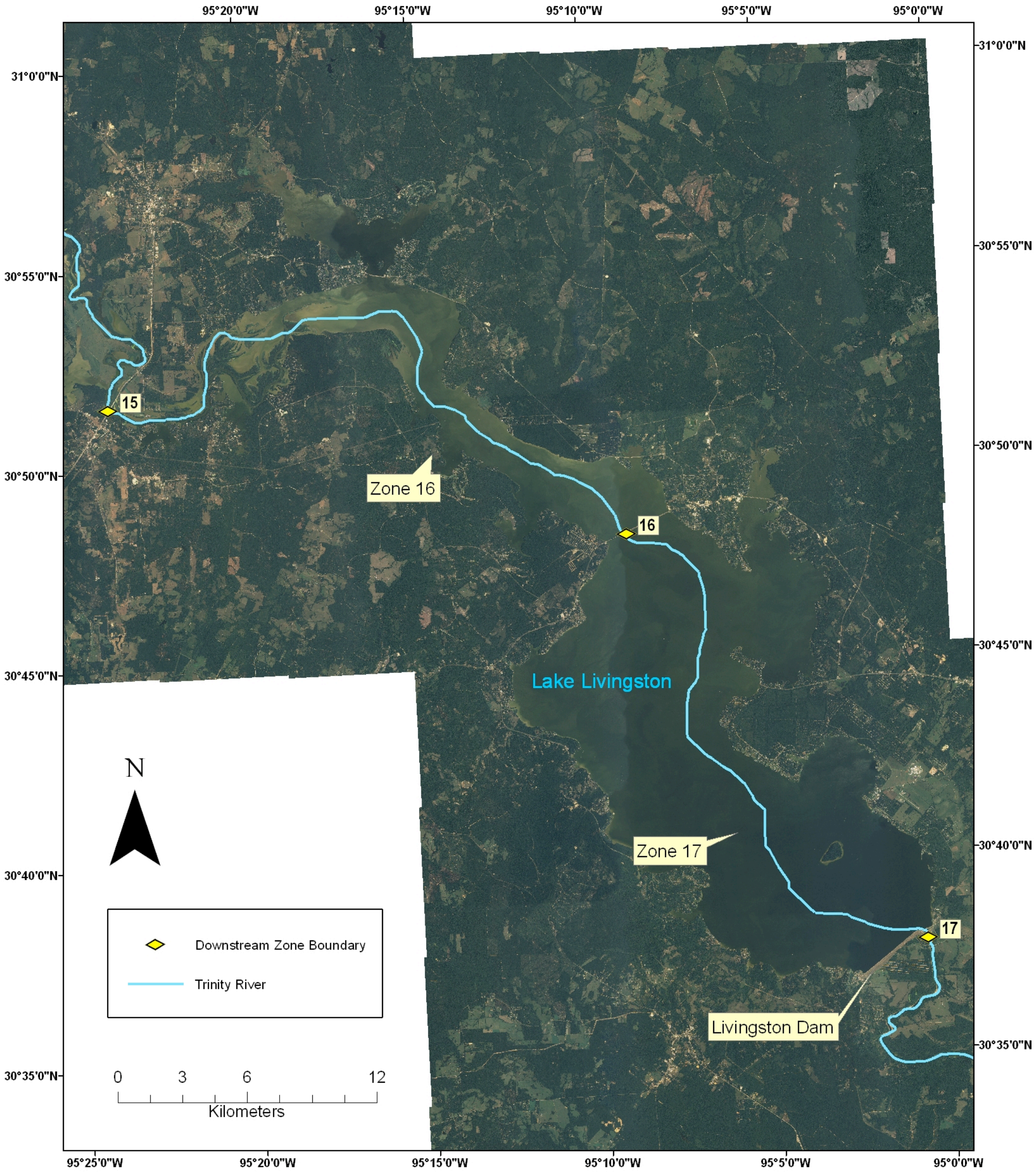
Trinity River - Zone 14



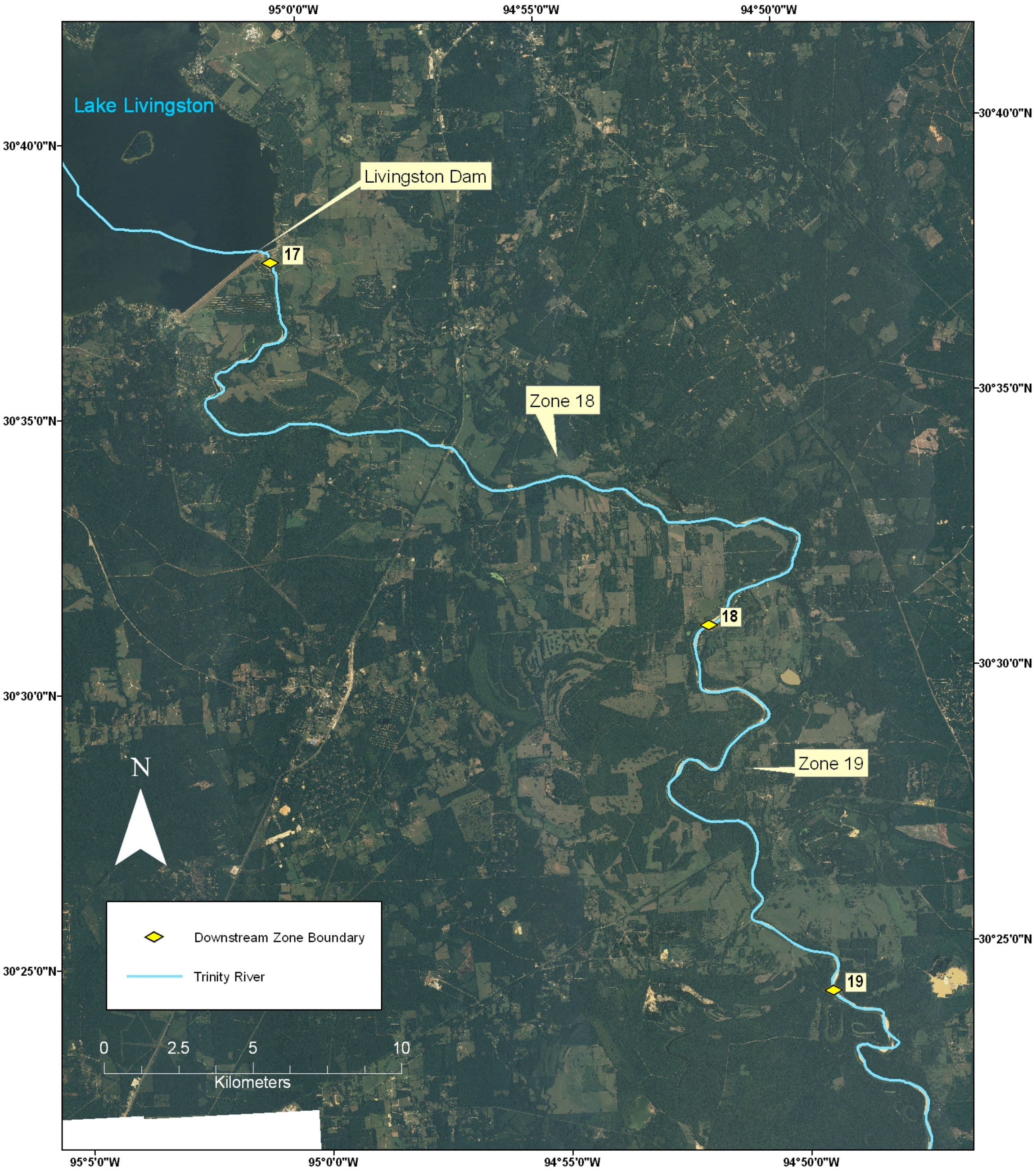
Trinity River - Zone 15



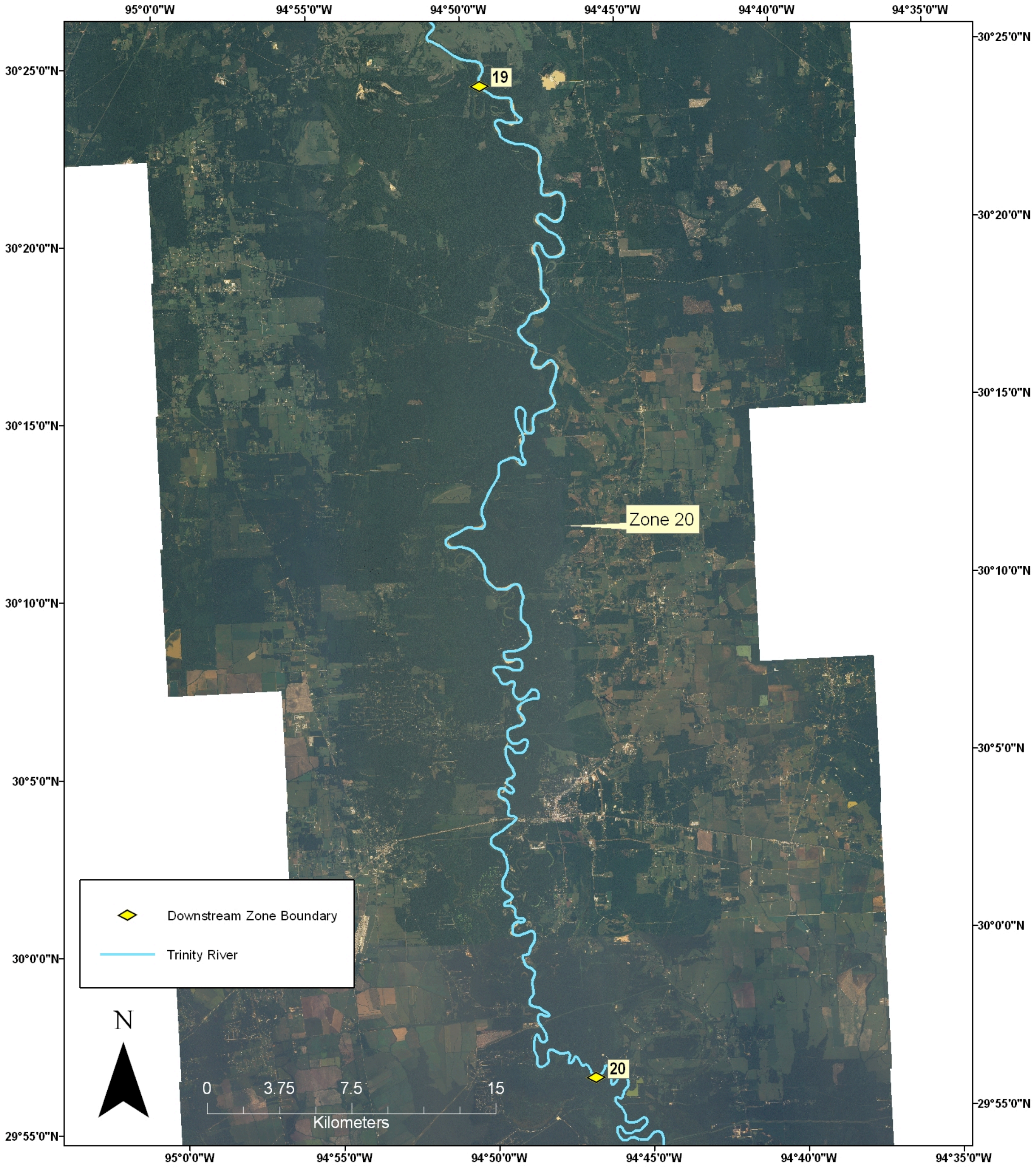
Trinity River - Zones 16 and 17



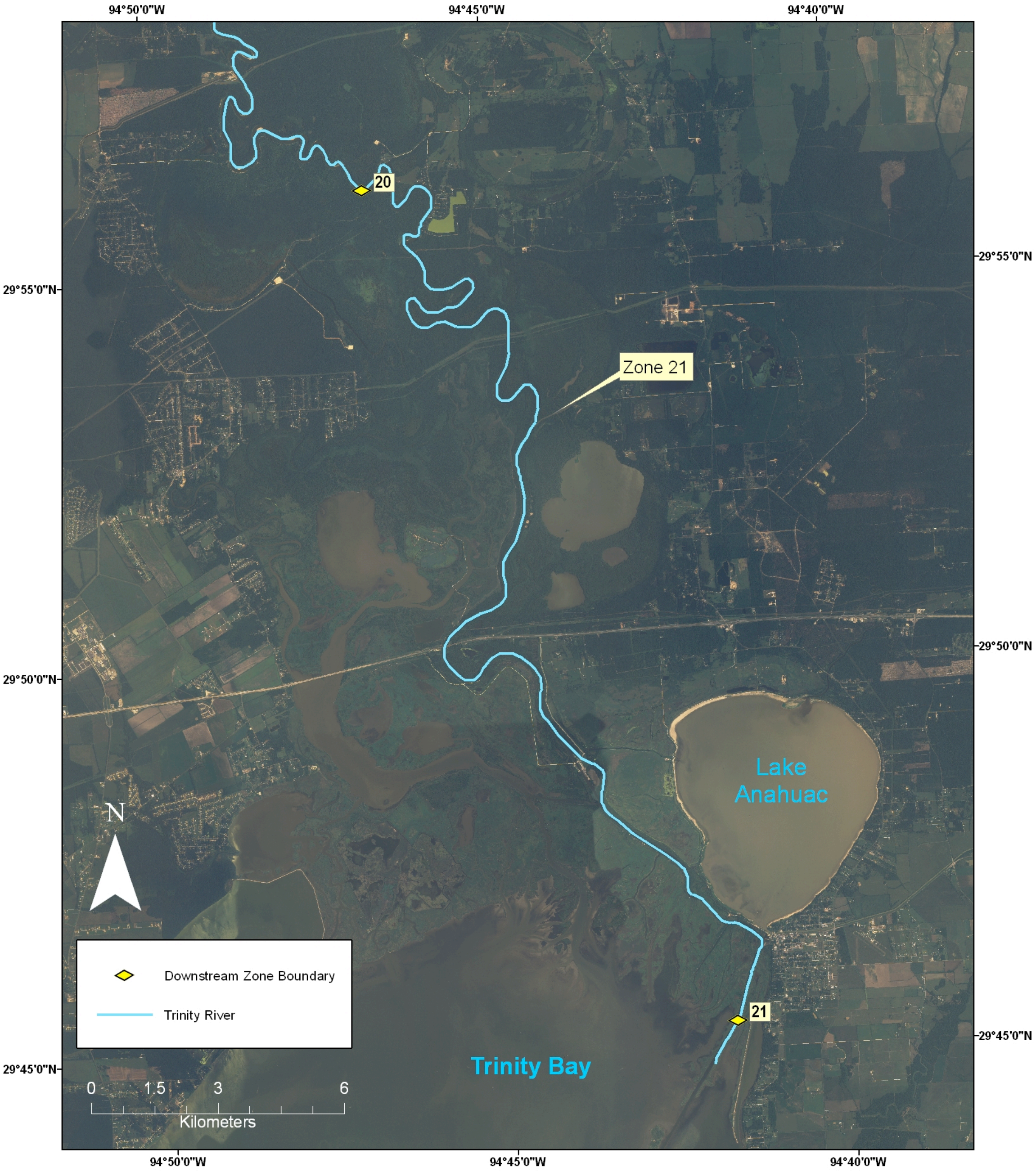
Trinity River - Zones 18 and 19



Trinity River - Zone 20



Trinity River - Zone 21



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Scope of Work

SCOPE OF WORK PLAN

Geomorphic Processes, Controls, and Transition Zones in the Middle and Lower Trinity River

Jonathan D. Phillips

August 2007

Overview

This work plan addresses a cooperative research study of the geomorphology of the Trinity River, Texas, from the confluence with the Elm Fork to Trinity 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 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 ccondition and behavior of the Trinity River.

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

(3) Classify the middle and lower Trinity (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.

- 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).

Personnel and Responsibilities

TWDB will oversee the activities of the project and serve as contract manager. Dr. Jonathan Phillips/Copperhead Road Geosciences (University of Kentucky, but functioning as an independent contractor) will be principal investigator, with research assistants. The University of Kentucky Geographical Information Systems Laboratory (Jeff Levy, under the supervision of Phillips) will be retained to perform some of the analyses, under a work-for-hire basis.

Tasks

(1) Literature Review
(2) Acquisition of data
(3) DEM and morphometric/topographic analysis
(4) Analysis of hydrologic data
(5) Interpretation of DOQQ and DLG imagery and soil maps/data
(6) Field observations and data collection
(7) Synthesis, interpretation, and analysis of results from tasks 1-6
(8) Produce report
    8A: Initial zonation and maps
    8B: Full report