THE EFFECTS OF URBANIZATION ON CHANNEL MORPHOLOGY OF RIVERS IN TEXAS

A Dissertation

by

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ABSTRACT

The response of river morphology to channel and watershed alteration is an important body of research in which Coastal Plains Rivers have historically been underrepresented. Coastal Plains Rivers in North America flow through multiple, terraced floodplains resulting from cyclic transgression/regression episodes typically dating to the Oligocene. The rivers flow through self-formed, sand or silt bed channels valleys in passive-margin, tectonically stable areas. In North America, strong seasonal variations in evapotranspiration and rainfall produce drastically different hydrologic seasons which create order of magnitude differences in wetted perimeter, width-depth ratios, and roughness values on the same reach from season to season. Within this setting, Texas has experienced population growth at rates surpassing the United States national average 15-fold (1997-2012), mostly in urban settings built on riverbanks. To understand and potentially predict the response of rivers in the Coastal Plains to the effects of increasing human population coupled with effects of associated climate change and variability, this study selects three rivers from the region which are heavily impacted by growing urbanization and assesses hydraulic and morphological characteristics upstream and downstream of urbanization.

The Brazos River near Waco, Texas, the Colorado River near Austin, Texas, and the Trinity River near Dallas, Texas, are investigated in this study. Beginning approximately six miles upstream of each respective urban center and continuing six miles downstream, stability is assessed using qualitative morphological indicators, stream power and unit stream power calculations, and sediment size comparison. Potential effects of alterations to sediment size on geomorphology and biogeomorphology are considered. A comprehensive review of the impact of land-cover alteration in watersheds and its direct effects on channel morphology, indirect effects on morphology through climate alteration, and varying impacts based on modification type is presented, with a discussion of land-cover types in each HUC-12 watershed studied. Finally, current methods of classifying Coastal Plains Rivers and assessing their stability are discussed, and modified methods proposed.

DEDICATION

This work is dedicated to two people. First, to the former committee member who called it unrealistic; who told me I was not a "real scholar". You were wrong.

Second, to any student who has received dismissal, rather than guidance, from advisors because he or she does not fit the mold of a traditional doctoral student. You can do it. Just keep pushing.

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I am indebted to Dr. John “Rick” Giardino, who enthusiastically took me on as a graduate student and gave me free reign to tackle this project. Thank you for your guidance.

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I am sincerely grateful to my field partner and husband, Mr. Mike Owens. When I described the field work to him and said I could use his help hauling equipment and paddling down (and up) major rivers, he jumped in without hesitation. This work would not have been completed in the timeframe it was without his assistance.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Dr. John R. Giardino (committee chair) of the Department of Water Management and Hydrological Sciences, Dr. John Vitek of the Department of Geology and Geophysics, Dr. Virender Sharma of the Department of Public Health, and Dr. George Allen of the Department of Geography.

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NOMENCLATURE

LCRA	Lower Colorado River Authority
LULC	Land use and land cover
Put-in	Location at which river is accessed
Take-out	Location at which river is exited
TWDB	Texas Water Development Board
USGS	United States Geological Survey

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CHAPTER I

INTRODUCTION

Section 1.1 Introduction

During the years 1997-2012, the population of Texas grew from 19.74 million to 26.08 million people. This growth rate is 15 times faster than the national average, and occurred mostly in urban settings (Lund, 2017; Ura and Daniel, 2018). Much growth centered around the Dallas-Fort Worth Metroplex (DFWM) and in the Austin area, cities built on the banks of the Trinity River and the Colorado River, respectively. Although humans have learned to adapt to long-term adjustment of rivers, major anthropogenic changes can reduce time scales for geomorphic change to decades or centuries (Simon and Rinaldi, 2006). It is imperative to understand the response of a river to changes to land use to predict fluvial activity in response to continued urbanization and potential needs for restoration (Bledsoe and Watson, 2000; Doyle et al., 2000; Gregory, 2006; Segura and Booth, 2010). Investigations of the effects of urbanization on rivers are numerous, but few have been conducted in regions with the climate (Köppen-Geiger Cfa: warm temperate, fully humid, hot summer), geology (predominantly limestone and shale, some sandstone), and topography of the Gulf Coast region of the United States. Further the effects of urbanization on river morphology has been studied at the scale of plot, field, and small watershed, but has yet to be fully determined at a larger scale (Wilcox et al., 2011). Given the current growth of and projections for population in the region, it is necessary to understand effects of urbanization on the major rivers in the Gulf Coast to prepare for fluvial adjustments induced by the rapid expansion of its urban centers.

In this study, a “stable” stream is defined as one which does not alter its geomorphology faster than would be expected for a stream in a similar geologic or climatic region (Doyle et al., 2000). Indicators of the morphological stability of river channels are many, and none should be taken on its own as sole evidence for channel condition. It is worthwhile, however, to investigate each as a contributor to the overall stability level of a river so that all its implications may be considered. Fischenich (2001) assesses the stability of a stream by how a river accommodates itself to inflowing water and sediment load and clarifies that a stable stream may adjust its boundaries but will not change its geometric character. This study measures stream power and unit stream power as indicators of river stability. Although shear stress has often been used to quantify channel stability in previous studies (Graf, 1983; Fischenich, 2001; Phillips et al., 2014), stream power may be a more effective indicator and is geomorphologically significant because it is directly related to total sediment transport. Because stream power is a function of channel dimensions and discharge, it is also more valuable in process analysis than are the individual channel dimensions considered separately (Graf, 1983).

Migration of a river channel is a function of stream power and sediment size (Nanson and Hickin, 1986), thus, sediment size is also an indicator of channel stability. Fine sediment is generally more cohesive than coarse, and so it follows that fine-grained channels will be more stable in natural rivers. One should not overlook, however, the role of coarse sediment in promoting channel stability, as coarse sediment encourages armoring (Lagasse et al., 1980). In assessment of morphological stability of river channels, sediment size is an important consideration for its influence on abiotic and biotic factors.

Fine sediment is attributed to lower water quality and increased suspended matter problematic for stream ecology. Both factors pose a threat of modification to biogeomorphic processes in the river channel.

Over the last century, expansion of urban centers and impervious areas in the southern United States has altered rivers of the Coastal Plains and also the hydrologic cycle within this already dynamic climatic region (O'Driscoll, 2010). Of the various methods by which humans alter their environment, change in land cover has the largest global impact (Brondizio et al., 2019). Even land left untouched is not immune to the effects of regional change in land cover; patches of undeveloped land have been fragmented to 990,000 bodies of land averaging a square kilometer in area, causing habitat disconnect and fragmentation of natural geomorphic processes (Jacobsen et al., 2019). This work reviews prior studies on the direct effects of change in land cover and engineering structures on hydrological processes related to river stability, as well as its indirect effects as a contributor to local and regional climate processes. Examples from the Brazos, Colorado, and Trinity Rivers in Texas are presented.

River channels, by nature, are dynamic entities prone to regular adjustment (Schumm, 1972; Rosgen, 1994; Thorne, 1996b). The problem which arises from excessive adjustment is primarily a threat to human interests, not the longevity of the river (Thorne, 1996b). Many assessments of river stability were developed to assess the structural integrity of engineering structures which cross river channels (Pfankuch, 1978; Brice, 1982; Brooks, 1987; Thorne et al., 1996 a and b; Johnson et al., 1999; Doyle et al., 2000; Lagasse et al., 2012). This study utilizes a method presented by Doyle et al. (2000), which is a modification of the method by Johnson et al. (1999), to assess the overall channel stability of the Brazos, Colorado and Trinity Rivers based on morphological indicators. This procedure was developed to determine stability of gravel-bed rivers at road crossings and culverts to avert bridge failure resulting from channel adjustment and was implemented on streams in Pennsylvania and Maryland, then modified by Doyle et al. (2000) for application to gravel streams in Indiana. The Doyle, et al. (2000) method offers an easy to use and efficient method of assessing channel stability based upon morphological indicators, and with simple modifications is well-suited to low gradient Coastal Plains Rivers.

Currently, no single classification provides a comprehensive characterization of Texas' Coastal Plain river systems (Hudson and Heitmuller, 2008). This work seeks to expound upon successful classification schemes already in use to make them more applicable to the low-gradient rivers of the Coastal Plains. This study reviews the history of contributions to river classification and focuses on those most commonly in use today, specifically the Rosgen classification system for natural rivers (Rosgen, 1994, 2009). Its advantages and drawbacks are addressed, specifically the oft-cited concern regarding uniformly determining bankfull stage of a river channel. I propose a modification of Rosgen's system which I believe is more easily and accurately implemented on low-gradient rivers and which I believe will remove considerable amounts of observer bias and data variability in diagnostic channel features.

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CHAPTER II

EFFECTS OF URBANIZATION ON STREAM POWER AND UNIT STREAM POWER

2.1 Introduction

This study investigates the effects of urbanization on stream power and unit stream power, for the purpose of assessing the effects of urbanization on the stability of a stream. In this study, a "stable" stream is defined as one which does not alter its geomorphology faster than would be expected for a stream in a similar geologic or climatic region (Doyle et al., 2000). Fischenich (2001) assesses stability of a stream by how a river accommodates itself to inflowing water and sediment load and clarifies that a stable stream may adjust its boundaries but will not change its geometric character. Although shear stress has often been used to quantify channel stability in previous studies (Graf, 1983; Fischenich, 2001; Phillips et al., 2014), stream power may be a more effective indicator (Graf, 1983; Fischenich, 2001; Phillips et al., 2014) and is geomorphologically significant because it is directly related to total transport of sediment (Bagnold, 1980). Because stream power is a function of channel dimensions and discharge, it is also more valuable in process analysis than are the individual channel dimensions considered separately (Graf, 1983). This study contributes to our knowledge of fluvial theory in areas which are currently lacking. For example, a lack of data exists relating stream power to stability (Fischenich, 2001). In addition, we do not fully understand the spatial characteristics of stream power, especially on the regional or network scale (Graf, 1983) and have not yet fully considered anthropogenic influences on stream power.

2.1.1 Stream Power and Stability of a Channel

The ability of flowing water to erode sediment determines potential alteration to the channel morphology and is directly correlated to stream power or unit (specific) stream power (Yang et al., 1972; Govers and Rauws, 1986; Phillips, 1989; Wohl, 2000; Fischenich, 2001; Stacey and Rutherford, 2007; Julian et al., 2012). Yang et al. (1972) developed a unitless equation for stream power to estimate total concentration of sediment in alluvial channels in consideration of variable particle size and water depth and temperature. Multiple researchers (Govers and Rauws, 1986; Govers, 1992; Magilligan, 1992; Ali et al., 2011) have found unit stream power to be a valuable predictor of the capacity to transport sediment. Parker et al. (2014) developed a ST:REAM model for the River Taff catchment in South Wales, UK which closely correlates features associated with erosion or deposition with values for stream power, although not consistently on a regional scale (Parker et al., 2014). Bizzi and Lerner (2015) also used stream power to predict where erosion or deposition will be the dominant force at work in a stream and showed that the dominant process (i.e., deposition or erosion) can be determined by local stream power and stream power upstream. Deposition is more likely to occur when local stream power was notably lower than that in upstream segments, and erosion more likely to occur when local stream power was higher than stream power above (Bizzi and Lerner, 2015; Gartner et al., 2015). This observation offers insight to how, specifically, a channel responds to outside forces, based upon stream power.

Wu et al. (2018) found that capacity to transport loess was well predicted by unit stream power on slope gradients above 26.79% and was often a better predictor than shear stress at different gradients in non-erodible conditions (Wu et al., 2016; Wu et al., 2018). Such conditions are rarely encountered in nature, except when channelization has been introduced, as is often found in urban rivers. Candel et al. (2018) utilized potential specific stream power in paleochannels to correlate periods of high potential specific stream power to increased channel migration. When relating stream power to adjustment of a channel, consideration is always taken of external forcings. It is not satisfactory to assume that erosion or deposition is linearly related to stream power or unit stream power in every fluvial setting (Whipple and Tucker, 1999; Fonstad, 2003), but a sufficiently strong correlation exists for consideration as a stability indicator (Yang et al., 1972; Govers and Rauws, 1986; Govers, 1992; Doyle et al., 2000; Fischenich, 2001; Ali et al., 2011; Bizzi and Lerner, 2015; Gartner et al., 2015; Wu et al., 2016; Candel et al., 2018; Wu et al., 2018).

In general, values of stream power and unit stream power decrease with increasing stability and vice versa (Abernethy and Rutherfurd, 1998; Doyle et al. 2000). Prior qualitative assessment shows decreased stability downstream of urbanization in all three rivers, thus, it is hypothesized that stream power will be higher downstream of urbanization than upstream. In lab experiments, sand-bed channels not affected by urbanization demonstrate reduced stream-power on downstream reaches compared to upstream reaches because of the effects of seepage (Sreenivasulu et al., 2011). It is hypothesized that the influence of urbanization on these three rivers is sufficiently great to overshadow the effects of seepage.

2.1.2 Role of Land Usage and Land Cover in Stream Power

Alterations to land use and land cover (LULC) have direct effects on the components of stream power, but those effects vary by channel and watershed. A great deal of modern LULC alteration is in the form of conversion of native landcover to urban setting or farmland. This often increases discharge by increasing runoff and decreasing infiltration and evapotranspiration in the watershed (Schlesinger et al., 1990; Zhang and Schilling, 2006; Suriya and Mudgal, 2012; Wijesekara et al., 2012; Nugroho et al., 2013; Quyen et al., 2014; Zhu et al., 2014; Ahiablame et al., 2017). These changes are often most pronounced in studies of vegetated land cover converted to impervious cover. Some studies of conversion of one type of vegetation to another have proven inconclusive regarding changes to streamflow, indicating that a general relationship between change in land cover and streamflow is unlikely (Yan et al., 2013; Guzha et al., 2018). Still, conversion of even small amounts of native land cover to urbanized cover is a major contributor to increased streamflow (Miller, 2002; Nie et al., 2011; Wijesekara et al., 2012).

Although numerous studies have linked anthropogenic alteration of landcover to channel widening (Bryant et al., 1999; Fitzpatrick et al., 1999; Julian et al., 2012), others (Bartley et al., 2008; Faustini et al., 2009) find that the dominant response of some channels is a reduction in channel width. Booth (1990) notes two possible scenarios resulting from watershed urbanization: channel expansion, in which cross-sectional area increases proportionally to discharge increase, or catastrophic channel incision which results in changes far greater than the discharge increases that initiated them.

Studies of the Canadian River found that specific stream power was the dominant influence on channel widening and channel erosion (Curtis and Whitney, 2003; Julian et al., 2012). Notable feedbacks exist, however, between land usage and channel widening on a temporal scale (Julian et al., 2012). In the Julian et al. (2012) study, as land on the banks of the river was converted to agricultural use, the banks became more susceptible to erosion. A negative feedback loop developed whereby increased erosion from croplands caused an increase in active channel area, eventually causing a decrease in available cropland. In response, farmers reduced cultivation of floodplains, leading to another negative feedback loop: less land clearing and a wider channel promoted native vegetation growth on channel margins, eventually leading to channel narrowing (Julian et al., 2012). Similarly, construction of a hydroelectric/flood control dam was shown to cause a positive feedback loop between channel narrowing and vegetation growth. With the channel already narrowing because of increased vegetation growth, the dam reduced specific stream power further so that vegetation colonized the margins of inactive channels at an increased rate, promoting sediment deposition and further vegetation growth, resulting in continued narrowing of the channel.

Stream power is a function of stream discharge and slope. Conventionally, discharge increases from the headwaters of a stream to the mouth, whereas slope decreases. It logically follows that stream power should peak in the mid-profile range, and this is observed in some studies (Lecce, 1997; Knighton, 1999). This pattern is inconsistent, however, among rivers. Increase in discharge may be offset by changes to channel slope, width, roughness, or other factors (Phillips and Slattery, 2007). Some studies have found distributions of stream power with multiple peaks, scattered peaks, or even none at all (Graf, 1983; Magilligan, 1992; Fonstad, 2003; Reinfields et al., 2004; Jain et al., 2006). In the Henry Mountains of Utah, stream power decreased in the downstream direction during the 19th century because the region was experiencing region-wide deposition. This changed during the 20th century when, partially in response to catastrophic flooding, system-wide erosion dominated (Graf, 1983). In a study of the Sangre de Cristo Mountains of New Mexico, Fonstad (2003) found underlying geology to influence stream power at least as strongly as channel slope. Allen et al. (2013) found the same level of influence in the northwest Himalayas. Phillips and Slattery (2007), in their studies of the Lower Trinity River, found processes of streamflow were strongly influenced by antecedent topography and river and backwater forcings. Thus, a generalized model of stream power is unlikely; each river's characteristics must be considered individually.

2.1.3 Equations for Calculating Stream Power

The equation for cross-sectional stream power (Ω, Wm^{-1}) is

[Eq.1] $$\Omega = \gamma QS$$

where γ is specific gravity of water (9807 N/m^3), Q is discharge (m^3s^{-1}), and S is channel slope (Reinfields et al., 2004; Phillips and Slattery, 2007). Various equations have been developed to determine channel discharge when direct measurement is unreliable. Three equations for velocity are used in this assessment, offering three separate calculations of channel discharge to be used in calculation of stream power and unit stream power.

All calculations are based on a channel at bankfull stage. Bjerklie (2007) presents several equations for calculation of bankfull velocity (V_b). The first utilized in this study is:

[Eq. 2] $$V_b = 0.8 \sqrt{(g\lambda S)}$$

where g is acceleration due to gravity, λ is meander length, and S is the friction slope, assumed to be water surface slope at bankfull stage. This value is then multiplied by channel area (A) to determine channel discharge. This is the simplest equation offered by Bjerklie (2007), but the recommended equation for calculating bankfull velocity in his study is:

[Eq. 3] $$V_b = \sqrt{[(2gS\,\lambda^*)/m]}$$

where m is an arbitrary fraction of the meander length, comparable to Manning's n in the Manning resistance equation (Bjerklie, 2007). Use of m allows for definition of flow conditions from data observable in remote imaging as opposed to the depth variable, used in the Manning equations. The variable m is calculated by:

[Eq. 4] $$m = 9.67\ (S\ \lambda^*)^{0.36}$$

where λ^* is meander length, estimated by multiplying meander wavelength by sinuosity. Velocity was also calculated using Manning's equation:

[Eq. 5] $$v = (R^{0.67} * S^{0.5})/n$$

where n is Manning's Roughness Coefficient, determined for each unique channel, R is hydraulic radius (m) and S is channel slope. Coefficient n was determined for each reach using guides by Arcement and Schneider (1989) and Charlton (2015). R and S were measured from field data.

2.2 Study Areas

The Brazos, Colorado, and Trinity Rivers in Texas are studied in the vicinity of Waco, Austin, and Dallas, respectively (Figure 1).

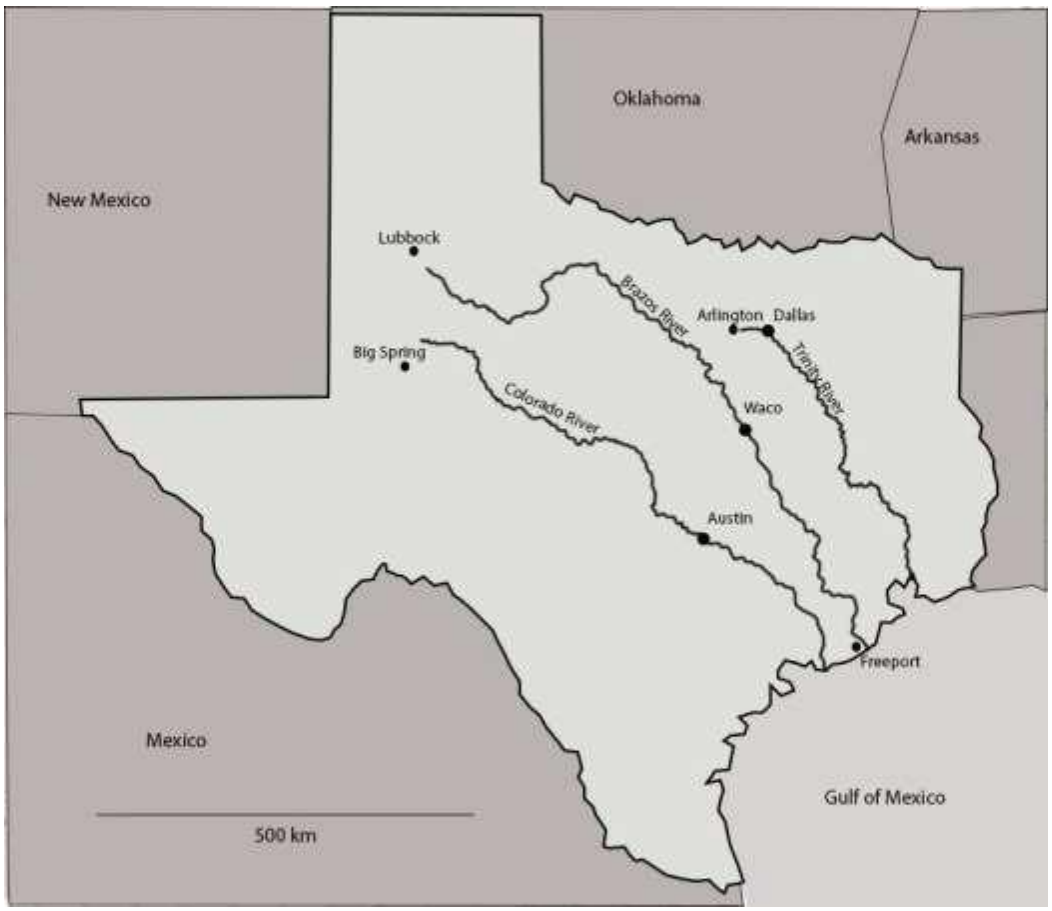

Figure 1: Location of three study rivers.

2.2.1 Brazos River at Waco, Texas

The Brazos River extends 1,352 km from the confluence of its Salt Fork and Double Mountain Fork in Stonewall County to its mouth in the Gulf of Mexico near

Freeport in Brazoria County (Hendrickson, 2019). The longest river in Texas, the Brazos River has the highest average annual discharge of any Texas river at 7.4 km^3/s (Texas State Historical Association, 2018; Hendrickson, 2019). This study examines a ~27 km reach beginning ~12 km upstream of the city of Waco and extending ~11 km downstream of Waco (Figure 2). Waco has an estimated population of 268,696 as of 2017 (United States Census Bureau, 2018), and the Brazos River flows directly through the city. Near Waco, the Brazos River flows through Cretaceous-aged Austin Chalk, the Wolfe-City Formation, and the Ozan formation. These units exhibit interbedded limestone, marl, sandstone, and clay.

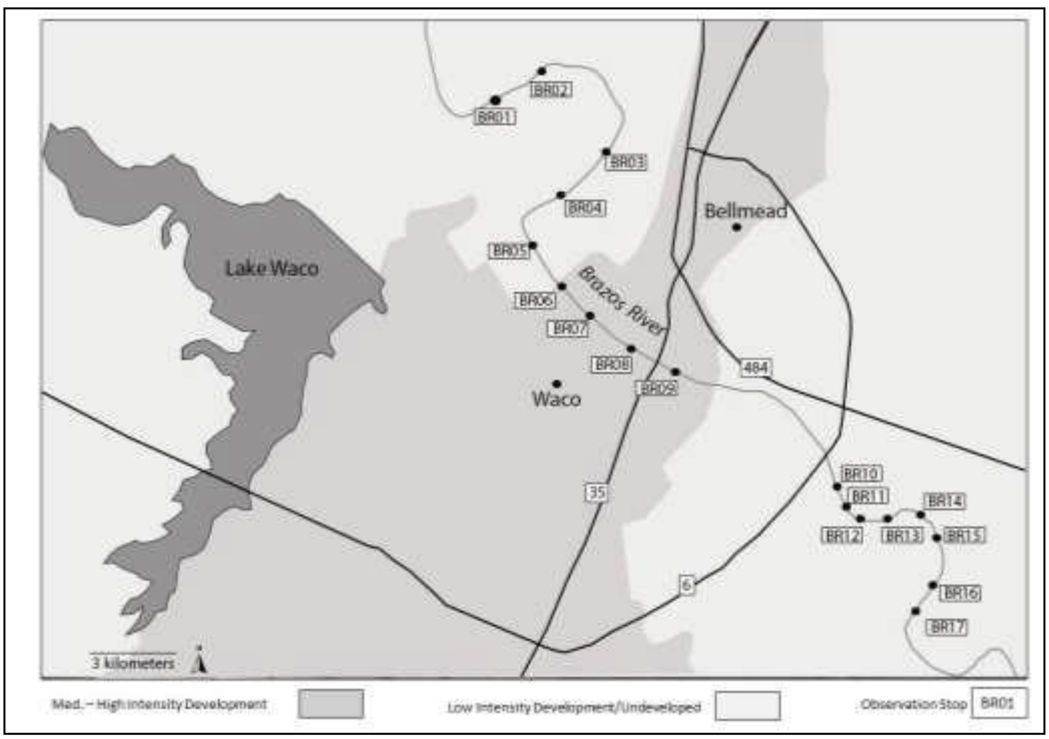

Figure 2: Locations of observations on the Brazos River near Waco, Texas.

This reach of the Brazos River flows through a modified stretch in Waco where the channel has been often reinforced with stone or wood and vegetation cleared (Figure 3).

Figure 3: Brazos River channels within Waco, Texas.

Upstream of Waco, the river flows through natural alluvium or limestone bedrock channels (Figure 4).

Figure 4: Brazos River channel upstream of Waco, Texas.

Immediately downstream of the most urbanized reach, Lake Brazos Labyrinth Weir manages water levels for flood control. (This dam should not be confused with the nearby Lake Waco Dam, which crosses the Bosque River.) The Brazos River Authority does not release water from dams in anticipation of excess precipitation, but in response to upstream and in-city gage readings (Brazos River Authority, 2019). Downstream of Waco, the Brazos River channel flows as an unmodified or lightly modified alluvium channel (Figure 5).

Figure 5: Brazos River downstream of Waco, Texas

Upstream river access was at Brazos Park East. River flow levels allowed paddling downstream and upstream with considerable effort, thus no separate take-out was used. Downstream of Waco, put-in and take-out was near the Hwy-6 overpass, where flow levels again allowed for returning by paddling upstream with effort (Figure 6).

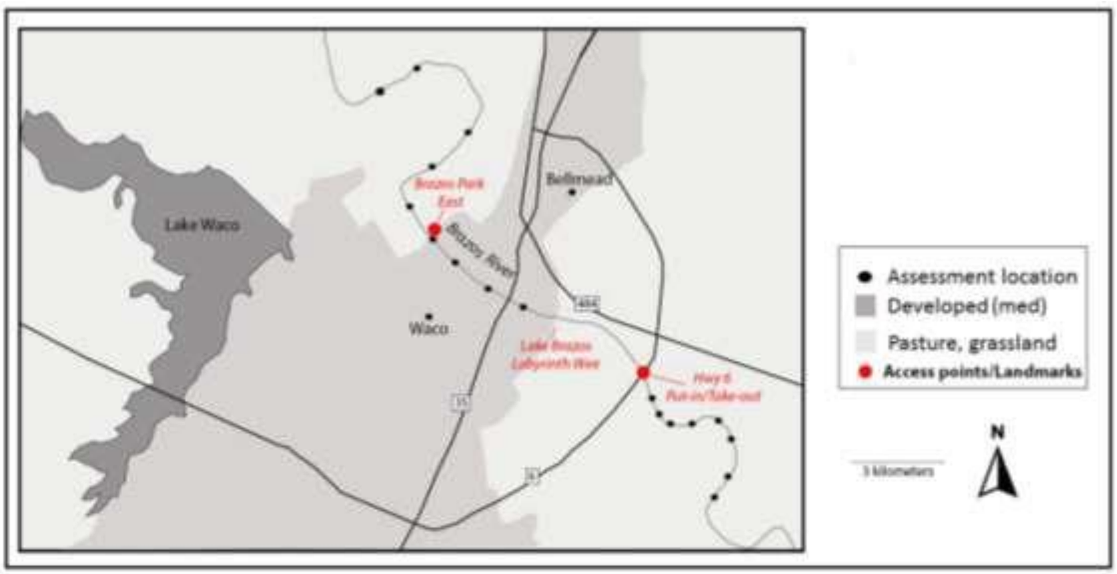

Figure 6: Access points and landmarks on the Brazos River near Waco, Texas.

2.2.2 Colorado River at Austin, Texas

The Colorado River extends 1,387 km from its headwaters near Big Spring, Texas, to the Gulf of Mexico and has a total drainage area of 103,341 km2 (Kammerer, 1987). This study assesses the river in the vicinity of Austin, Texas. Austin has a population of 950,715 as of 2017 (United States Census Bureau). The Colorado River in the observed reaches cuts through the Cretaceous-aged Upper Glen Rose Limestone (limestone, dolomite, and marl), the Fredericksburg Group (limestone, dolomite, and chert), and Austin Chalk. Channel slope in the study reaches is ~.0006. Average annual discharge of the Colorado River is 2.34 km^3/s (Texas State Historical Association, 2018).

Urban sprawl associated with Austin extends significantly to the northwest, following the Colorado River upstream. For this reason, observations of the river in a natural state upstream of Austin urbanization and suburbanization had to occur near Smithwick, Texas, approximately 50 miles (80.5 km) northwest of Austin (Figure 7).

Figure 7: Location of access points and study reaches of the Colorado River near Austin, Texas.

Despite the distance, the Colorado River in Smithwick flows through the same geology and climate as in Austin, and thus, allows for comparison of channel morphology before the effects of urbanization (Figures 8, 9). Put-in for the upstream reach was at the Shaffer Bend Recreational Area, managed by the Lower Colorado River Authority (LCRA) and take-out was at the Grelle Recreational Area, also managed by the LCRA.

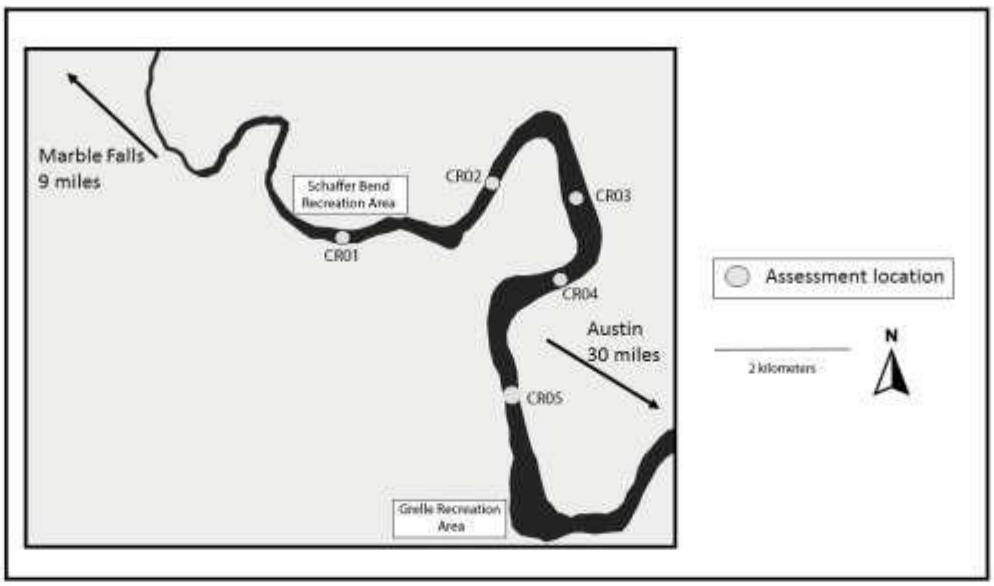

Figure 8: Access and observations points on the Colorado River upstream of Austin, Texas. Landcover on this stretch of river is unmodified or has low-impact development.

Figure 9: Colorado River channel upstream of Austin, Texas.

Two dams affect the Colorado River near Austin. Mansfield Dam creates Lake Travis, about 30 km upstream of Austin, and Longhorn Dam creates Lady Bird Lake in the Austin city limits (Figure 7). The river flows for approximately 43 km between the two dams, through heavily suburbanized and urbanized channel reaches. The suburban reaches have been continuously stabilized using wood or stone, and flow through alluvium or limestone bedrock channels. Interestingly, much of the urban reaches exhibit no or minimal stabilization, though wood and concrete stabilization does exist in some areas (Figures 10 and 11). Access to the river in Austin is readily available at the I-35 overpass or farther upstream at Rowing Dock, a canoe and paddle board rental business. Flow is slow enough that paddling both downstream and upstream is possible, thus no separate take-out location is necessary.

Figure 10: Colorado River channel in Austin, Texas, exhibiting wooden stabilization structures.

Figure 11: Other reaches of the Colorado River in Austin exhibited no channel stabilization structures, despite heavy urbanization. (Close-up of bank in bottom image).

The Colorado River was accessed downstream of Austin at the Roy G. Guerrero Park near Longhorn Dam. Access here is a favorite for kayakers, though accessing the river with a canoe is a challenge. Take-out was the FM-973 overpass (Figure 12).

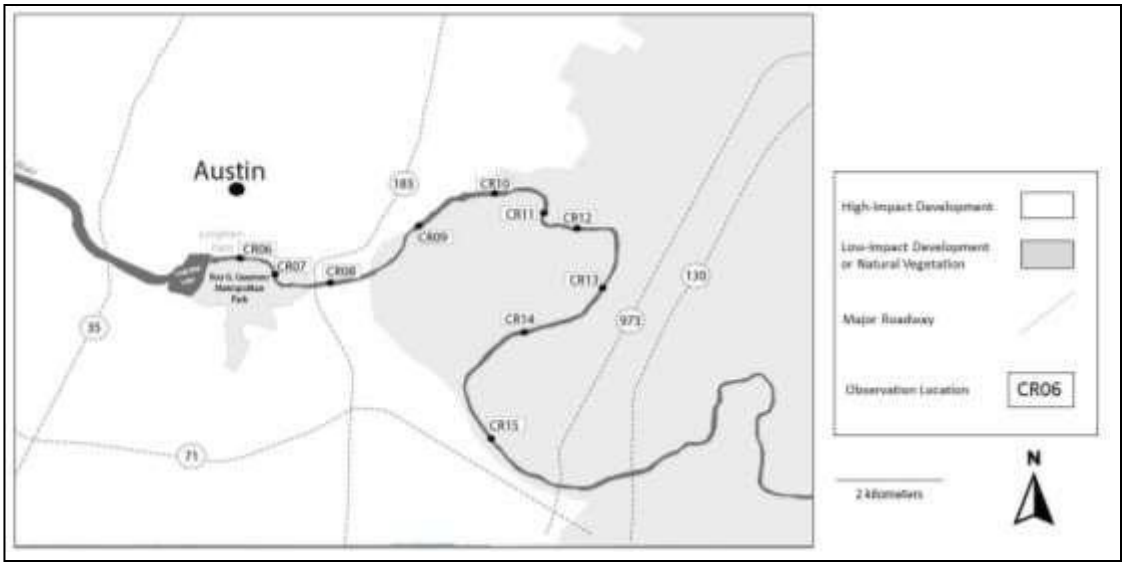

Figure 12: Observation locations downstream of Austin.

Downstream of Austin, the Colorado River flows through a natural channel with undeveloped banks (Figure 13).

Figure 13: Colorado River channel downstream of Austin, Texas.

Two locations in the study area create flow disruptions: a weir precariously placed beneath the US-183 overpass such that it does not appear on aerial photographs and surprises unsuspecting canoeists, and a recreational standing wave at a southward bend of the channel 10 km downstream of Longhorn Dam. Future researchers are advised to consult aerial photographs before canoeing this reach, because the placement of standing wave on a bend causes it to be out of sight until one is directly upon it.

2.2.3 Trinity River at Dallas, Texas

The Trinity River originates at the confluence of West and Elm Forks northwest of Dallas, Texas and east of Arlington, Texas. It extends 1,142 km to its mouth at Trinity

Bay in Chambers County, Texas. Average annual discharge is 7.03 km^3/s. In this study area, the Trinity River originates in Cretaceous-aged limestone, shale and sandstone of the Eagle Ford Group before flowing southwest through the Austin Chalk, lower Taylor marl, and calcareous silt and sand of the Neylandville and Marlbrook Marl formations, both of the Taylor group.

Assessment begins at the confluence of the West Fork and Elm Fork, marking the origin of the Trinity River main channel (Figure 14). Although this reach is geographically within an urbanized region of the Dallas-Fort Worth-Arlington metroplex, the channel is unaltered by engineering structures and retains a wide greenbelt on either bank extending nearly half a kilometer on each side of the river. As the river turns southwest through the city of Dallas, the greenbelt ceases to exist, and the channel is reinforced with concrete. At the Santa Fe railroad trestle, channelization ends as the river flows into the protected Great Trinity Forest and continues as a natural channel (Figure 15).

No dams are present on this stretch of the Trinity, although a constructed standing wave was emplaced at the Santa Fe railroad trestle. Though present for the first field excursion in May of 2018, this was removed during June-November 2018.

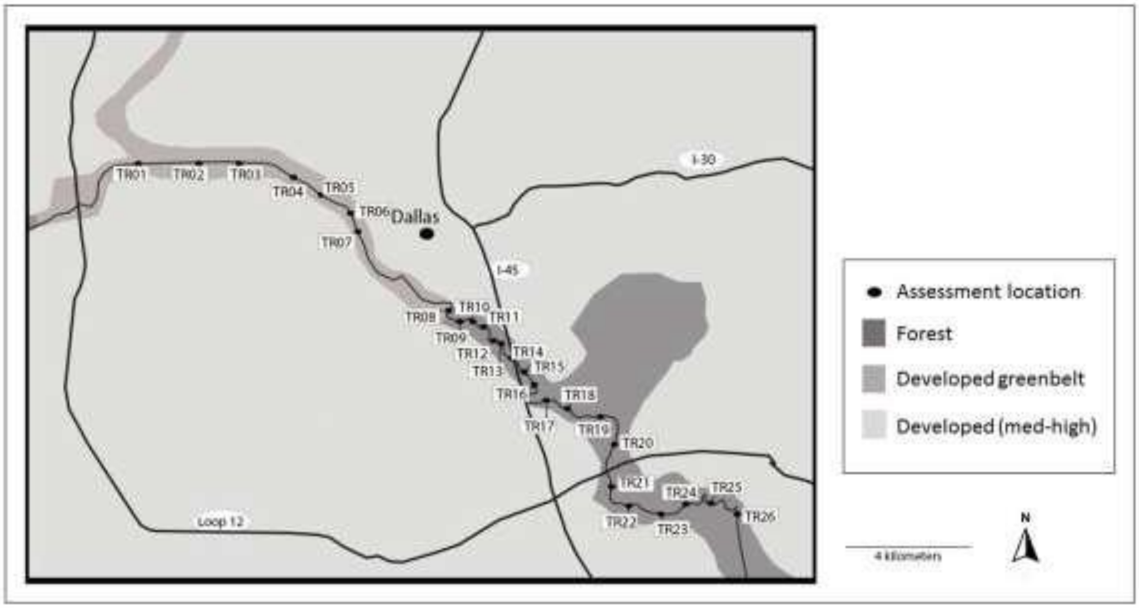

Figure 14: Observation stops on the Trinity River near Dallas, Texas

Figure 15: Trinity River channel upstream, within, and downstream of Dallas, Texas

2.3 Methods

Three rivers were selected for this study based on proximity to urban centers and accessibility. All three flow directly through a major Texas city before and after changing a more rural river setting, allowing for comparisons to be made between river stability before and after the effects of urbanization. Field data were collected by canoe. Pertinent equipment was a Garmin Striker 4 depth finder, GPS smart phone application, and Brunton® compass. As accessibility allowed, each river was traversed for 8-9 km upstream of the effects of urbanization, through the urbanized reach, and for 8-9 km downstream of urbanization. Even-spaced observations were made on straight reaches to avoid complicating effects of cutbanks and point bars. At each observation point, the width and depth of the channel were determined. At each bank, the height of the bank above water and bank slope were determined, and bank and bed sediment samples collected.

Field measurements were not obtained during periods of bankfull flow, thus values of bankfull were calculated based on observable field and remote sensing data. Channel cross-sectional area was determined using measurements taken in field with information from DEMs of the study area. At each observation point, bank height above the water level was determined using a Brunton® compass, tape measure and basic trigonometry, correcting for known standing and kneeling eye-height of the observer. Bank angle was measured at each site using the Brunton® compass. The channel was crossed by canoe and a GPS tracking application used to measure the traversed width in meters and ensure that a straight path was taken. Meanwhile, a Garmin® Striker 4 depth finder was used to determine channel depth at the edges of the channel and at equally spaced intervals across each channel. Using these field data, cross-sections of each stop from the current water height were drawn to scale in the lab. To determine the channel area at bankfull stage, DEMs of the study areas were consulted for elevation above sea level of the upper bank. Field calculations of the same bank height above water level and angle from water level on day of observation were used to reconstruct each channel. The hand reconstructions were compared with elevation profiles constructed from the DEM and corrections made, as necessary. SketchAndCalc ™ software was then utilized to determine the wetted perimeter, hydraulic radius, and cross-sectional area of each observation point at bankfull stage. Cross-sections are presented in Appendix A.

Channel reconstructions in tandem with elevations and reach lengths measured from DEMs allowed for measurement of water surface slope at bankfull stage. Meander length was measured from remote imagery. These values were input to a spreadsheet for calculation of stream power at each observation point, and vicinity to urbanization compared.

2.4 Results

Average values of stream power and unit stream power are presented in Table 1:

	Brazos River (U)	Brazos River (D)	Colorado River (U)	Colorado River (D)	Trinity River (U)	Trinity River (D)
Stream Power (Eq. 2)	5505.24	3616.83	798.2	20700.64	1534.75	583.43
Stream Power (Eq. 3)	3112.81	2275.34	1038.19	13302.57	996.23	473.32
Stream Power (Eq. 4)	2074	2011.1	1134.96	18305.92	1363.68	803.97
Unit Stream Power (Eq. 2)	40.2	34.06	2.3	163.86	25.75	11.97
Unit Stream Power (Eq. 3)	22.64	21.42	2.93	105.28	16.69	9.67
Unit Stream Power (Eq. 4)	15.05	18.36	3.2	143.63	22.60	16.25

Table 1: Average values of stream power (W/m2) and unit stream power (W) for three study rivers, upstream and downstream of urbanization.

Reliability of bankfull discharge values for each river were assessed by comparing calculated bankfull discharge with average of measured flood stage flow, recorded by the National Weather Service (NWS) and USGS. These data are presented in Table 2:

River	Flood Stage Flow (m^3/s), NWS/USGS	Calculated Qbf, m^3/s (Eq. 2)	Calculated Qbf, m^3/s (Eq. 3)	Calculated Qbf, m^3/s (Eq. 4)
Brazos	1854.8	2054.79	1502.68	1180.13
Colorado	976.9	1235.44	1013.72	1052.31
Trinity	272.7	209.46	183.22	302.3

Table 2: Flood stage discharge for each study river, based on data by the NWS and USGS. These values are compared to calculated bankfull values.

Equation 2 from Bjerklie (2007) most closely approximated measured flood stage discharge at the Brazos River, but as bankfull flow is just below flood stage, Equation 3 by Bjerklie (2007) may be considered the best approximation of bankfull flow for the Brazos River. All three equations returned rates of bankfull flow higher than the average measured flood stage at the Colorado River, but Equation 3 (Bjerklie, 2007) is the closest value. Equation 4 (Manning, 1891) returned the value of bankfull discharge closest to measured flood stage for the Trinity River.

Stream power and unit stream values for the Brazos River are presented in Figures 3 and 4. The Brazos River exhibits a notable drop in stream power immediately downstream of Waco. No hydroelectric or flood control dam is present in Waco, but a weir transects the river immediately downstream of Baylor University and creates a recreational area known locally as Lake Brazos.

Figure 15: Stream power values, Brazos River near Waco. Red background indicates stops upstream of Waco and green background indicates stops downstream of Waco.

Figure 2: Unit stream power values, Brazos River near Waco.

Calculated stream power and unit stream powers for the Brazos River near Waco are presented in Table 3, based on velocity calculated from three different equations.

	Stream Power (Eq.2)	Stream Power (Eq.3)	Stream Power (Eq.4)	Unit Stream Power (Eq.2)	Unit Stream Power (Eq.3)	Unit Stream Power (Eq.4)
Stop 1	4435.40	2354.26	1291.188	33.13957754	17.59	9.64725
Stop 2	4032.16	2140.22	1255.165	30.55364221	16.22	9.510986
Stop 3	5260.20	2792.05	1755.133	42.65145381	22.64	14.23119
Stop 4	6164.88	3272.24	2152.855	44.31655313	23.52	15.47592
Stop 5	7432.54	3945.10	2712.415	47.64145078	25.29	17.38616
Stop 6	5706.22	4172.99	3277.272	41.82528688	30.59	24.02164
Stop 7	2422.91	1524.25	968.9274	25.20713665	15.86	10.08039
Stop 8	3071.43	1932.23	1590.969	35.92732803	22.60	18.61
Stop 9	1859.12	1169.57	593.8615	17.90195094	11.26	5.718455
Stop 10	3241.40	2039.16	1638.049	36.99380701	23.27	18.69493
Stop 11	8413.63	5293.01	6230.822	64.60097706	40.64	47.84108
Stop 12	2692.47	1693.83	1043.998	23.70548531	14.91	9.191744

Table 3: Values for stream power (W/m^2) and unit stream power (W) for each stop on the Brazos River, using values for velocity calculated with three equations.

Stream power and unit stream power data for the Colorado River near Austin are presented in Figures 16 and 17. The Colorado River exhibits an increase in stream power and unit stream power downstream of Austin. Between the upstream observation points and the downstream points, two hydroelectric and flood control dams disrupt flow.

Figure 16: Stream power values (W/m2) for the Colorado River near Austin, Texas.

Figure 17: Unit stream power (W) for the Colorado River near Austin, Texas.

Calculated stream power and unit stream powers for the Colorado River near Austin are presented in Table 4, based on velocity calculated from three different equations. Stream power and unit stream power data for the Trinity River near Dallas are presented in Figures 6 and 7. The Trinity River exhibits a decrease in stream power and unit stream power downstream of Dallas. Between the upstream observation points and the downstream points, no dams or weirs disrupt flow. Calculated stream power and unit stream powers for the Trinity River near Dallas are presented in Table 5, based on velocity calculated from three different equations.

	Stream Power (Eq.2)	Stream Power (Eq.3)	Stream Power (Eq.4)	Unit Stream Power (Eq.2)	Unit Stream Power (Eq.3)	Unit Stream Power (Eq.4)
Stop 1	496.0077856	688.36	784.17	2.544021058	3.530589	4.02
Stop 2	812.8905079	1128.13	1051.86	1.854009597	2.572992	2.40
Stop 3	773.0222736	1016.41	1116.20	2.505257563	3.294039	3.62
Stop 4	1593.827456	2098.99	2453.65	2.978448676	3.922474	4.59
Stop 5	315.7461803	259.08	268.94	1.640069501	1.345737	1.40
Stop 6	37335.16643	23818.72	40900.21	255.8429824	163.2202	280.27
Stop 7	9875.244613	6973.41	5593.82	72.38323399	51.11346	41.00
Stop 8	19153.04356	13477.90	14699.17	115.0263862	80.94348	88.28
Stop 9	30469.09707	17979.89	28009.25	240.0653724	141.6632	220.68
Stop 10	26018.17739	15353.39	21121.07	196.4525626	115.9272	159.48
Stop 11	14992.19661	10106.63	13920.53	181.4376935	122.3119	168.47
Stop 12	25360.24746	17096.01	24820.56	189.2838293	127.6012	185.26
Stop 13	7373.128687	4760.77	4047.44	86.95752668	56.14778	47.73
Stop 14	15729.43595	10156.37	11633.11	137.2670909	88.63226	101.52

Table 4: Values for stream power (W/m2) and unit stream power (W) for each stop on the Colorado River, using values for velocity calculated with three equations

Figure 18: Values for stream power (W/m²) for the Trinity River near Dallas, Texas.

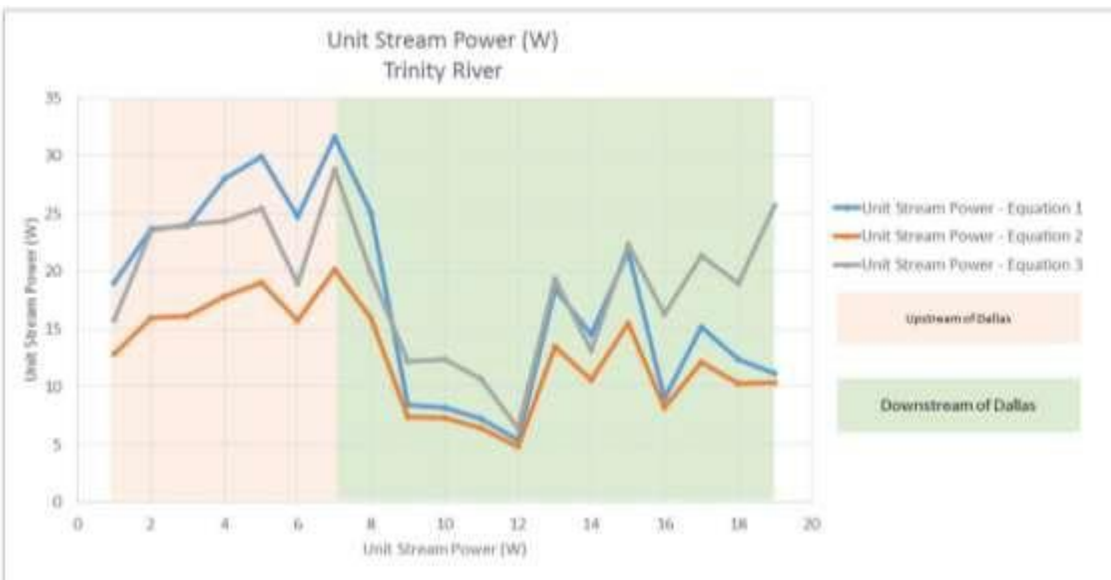

Figure 19: Values for unit stream power (W) for the Trinity River near Dallas, Texas.

	Stream Power (Eq.2)	Stream Power (Eq.3)	Stream Power (Eq.4)	Unit Stream Power (Eq.2)	Unit Stream Power (Eq.3)	Unit Stream Power (Eq.4)
Stop 1	972.0088197	655.52	810.9045	18.991966	12.808109	15.84417
Stop 2	1757.841145	1185.48	1743.797	23.67462821	15.966079	23.48547
Stop 3	1627.149766	1097.34	1641.061	23.90055473	16.118443	24.10489
Stop 4	1538.480594	977.26	1332.436	28.03353852	17.807172	24.27908
Stop 5	1764.618453	1120.90	1500.329	29.89358722	18.988693	25.41638
Stop 6	992.8922622	630.69	760.4051	24.7418954	15.716289	18.94855
Stop 7	2094.902191	1330.70	1906.105	31.64982914	20.104274	28.79748
Stop 8	1530.107056	971.94	1214.42	25.12078569	15.956964	19.93794
Stop 9	501.34197	438.55	723.5714	8.452907941	7.394214	12.19982
Stop 10	359.1181532	319.01	542.3722	8.193432653	7.278456	12.37445
Stop 11	362.9359464	322.41	534.928	7.258718928	6.448124	10.69856
Stop 12	218.9761173	194.52	261.3728	5.386866353	4.785305	6.429835
Stop 13	798.5966642	582.56	836.6892	18.46466276	13.469601	19.34542
Stop 14	798.0178032	582.14	724.1661	14.48834065	10.568954	13.14753
Stop 15	998.8019732	711.60	1026.62	21.74144478	15.489661	22.34698
Stop 16	439.024329	398.11	794.7172	9.014873286	8.174836	16.31863
Stop 17	708.0544118	566.46	994.4303	15.17801526	12.142838	21.31683
Stop 18	563.0271815	469.28	861.5829	12.37150476	10.311476	18.93173
Stop 19	669.8018932	621.93	1543.174	11.12997496	10.334463	25.64264

Table 5: Values for stream power and unit stream power for the Trinity River near Dallas, Texas

2.5 Discussion

At the Colorado River, the hypothesis of higher values of stream power and unit stream power downstream of urbanization compared to upstream was supported. This likely results from input of tributaries combined with river management. Three dams were built on the Colorado River between the observations upstream of urbanization and those downstream: Mansfield Dam at Lake Travis, Tom Miller Dam and Longhorn Dam at Lady Bird Lake. All three dams are hydroelectric and flood control structures, and thus, maintain a regular schedule of impoundment and release to satisfy electric needs of the city of Austin. The city of Austin provides drinking water for its residents from the Colorado River. Downstream values for stream power and unit stream power fluctuated, primarily because the cross-sectional channel area varied widely. The spike in stream power within Austin may be attributed to reduced channel roughness, because the river is maintained for recreation.

At the Brazos River and the Trinity River, stream power and unit stream power decreased downstream of urbanization. This does not support the initial hypothesis of increased stream power downstream of urbanization, but is in line with findings from other studies of stream power and unit stream power which found that stream power did not necessarily increase as one progresses downstream (Graf, 1983; Magilligan, 1992; Fonstad, 2003; Reinfields et al., 2004; Jain et al., 2006; Phillips and Slattery, 2007). In a natural condition, it is reasonable to hypothesize that stream power will increase to a maximum mid-longitudinal profile, because at this point the combination of slope and discharge have each reached their maximums. In a natural setting, discharge will continue to increase from the mid-point to the mouth of the stream, but the effects of decreasing channel slope prevent certainty of increasing stream power. In the case of a modified river, such predictions cannot be made with any degree of certainty. Even under natural conditions, surface slope varies between flows (Phillips and Slattery, 2007). In modified river channels, the effects of dams, weirs, and localized pumping amplifies variation in slope. Further, usage of bankfull flow as the reference discharge for such comparison is not without concern. The advantage of its usage is that, theoretically, the bankfull conditions are a uniform reference point within a specific river, but in reality this is not always the case. The return period for bankfull flow, for example, is variable and may even vary within the same river (Roper, 2008). Authors have long questioned the use of bankfull conditions as reliable reference variables (Pickup and Warner, 1976; Williams, 1978; Castro and Jackson, 2001). In an assessment of river stability, usage of projected bankfull conditions may be a misleading choice, because the river does not run at bankfull stage on a day-to-day basis. The standard condition of the river, in other words, is not assessable by considering its bankfull conditions, because these will always indicate an atypical, temporarily unstable conditions. The better alternative may be to assess the same river for an extended period of time and assess the adjustment of pre-urbanized and post-urbanized reaches to day-to-day weather events.

It was hypothesized that stream power values and unit stream power values would increase downstream of urbanization, because urbanization is often associated with lower stability of a stream and stream instability is associated with higher values of stream power (Doyle et al., 2000). Prior qualitative assessment of these same three rivers based on the modified Johnson et al. (1999) method, developed by Doyle et al. (2000) indeed found decreased morphological stability downstream of urbanization (Figure 20).

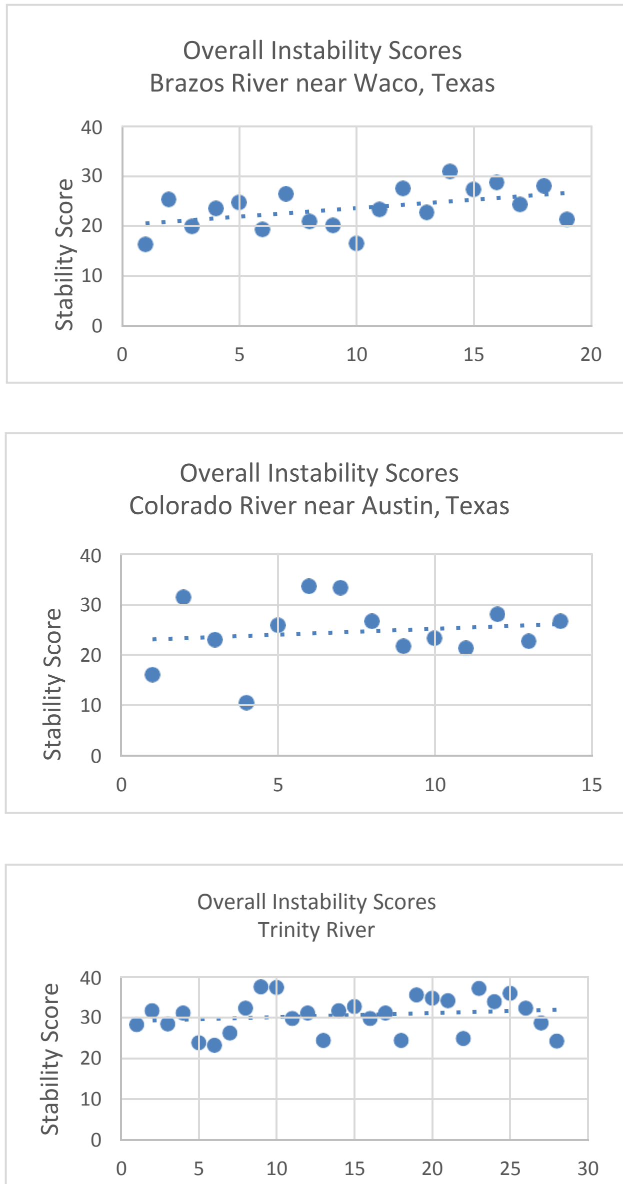

Figure 20: Qualitative instability scores for the three study rivers from observation points upstream of urbanization, through the urban center, and downstream of urbanization. Higher score indicates lower stability.

The instability rankings, represented in Figure 8, considered morphological indicators of channel stability such as excessive bank erosion (indicated by exposed roots, no or young vegetation, or leaning vegetation) and flow disruptors or channel debris. They provide a snapshot in time of the morphological stability of the river channel.

Observations were not conducted immediately after extreme rainfall to ensure that the state of the channel on the day of observation was representative of its typical state. The observed state, then, represented the channel as it had adjusted itself to current conditions wrought by natural and anthropogenic forces. Here is where stream power calculations, based upon predicted bankfull-stage conditions, present an over-simplification of the fluvial system. Calculations of bankfull discharge, used in stream power determination, rely on some channel characteristics that vary only slightly with time (cross-sectional area, channel slope, hydraulic radius) but others that will change with season and with anthropogenic influence (water surface slope, velocity, roughness). To assume a natural river without human modification, the more dynamic variables might be predicted from seasonal records of precipitation, snowmelt, vegetation growth, or seasonal ecosystem engineering. Anthropogenic influence adds more variables which often occur in reaction to, or in anticipation of, the aforementioned seasonal factors. Flood control dams will alter predictable seasonal high flows, surface water slope, and channel slope. Hydroelectric dams, with daily scheduled releases and impoundments, may create alternating high flow and low flow conditions that bear no semblance to flows predicted by seasonal runoff data. Predicted channel roughness changes from seasonal vegetation blooms and die offs may be altered by runoff of nutrients, fertilizers, or herbicides.

Management practices are fluvial events, and as such disrupt position and magnitude of power trends (Fonstad, 2003). Yet traditional calculations of bankfull flows do not consider anthropogenic influence, erroneously assuming that traditional hydraulic variables interact in a predictable and consistent manner that can be applied to most, if not all, rivers.

It has been said that wilderness is dead (Wohl, 2013). Opportunities no longer exist to investigate avenues of Earth which are not either distantly affected or directly managed by human influence. River management is now a daily reality and should be treated as a fundamental component of river stability, weighted equally to traditionally considered components such as discharge and shear stress. This is a dynamic component which may prove challenging to quantify. Other anthropogenic influences related to urbanization may be more temporally stable: channelization will predictably alter the roughness coefficient, altering flow velocity; land cover alteration of the watershed will alter rates of surface runoff and amount of groundwater contribution in a predictable manner; the effect of the urban heat island will create localized weather patterns which, in time, will become established and predictable. Management practices, however, result in variations in downstream flow which are less predictable because they vary based upon policy and location. Although methods of assessing river stability abound for those involved in river management, the effects of management practices themselves have not yet been considered in published assessments of river stability.

Further work needs to be done to quantify the role of river management practices in assessments of river stability. Consideration should be given to whether water releases from dams are scheduled in anticipation of impending precipitation, or whether they are executed in response to upstream stream gages. In either case, how much water is released relative to the overall input? Frequency and magnitude of release directly impact the flashiness of downstream flow, already an observed effect of urbanization (Lei and Zhou, 2018).

2.6 Conclusion

Stream power and unit stream power of three major urban rivers in Texas were investigated for the purpose of assessing the effects of urbanization on stability of a stream. Although it was hypothesized that stream power would increase downstream of urbanization, this hypothesis was not consistently supported. It is proposed that in additional to the standard physical fluvial components often assessed in river stability studies, river management practices be quantified and included in future river assessments. A future research need is to quantify river management with consideration of dam storage, scheduled frequency and magnitude of release from dams, and policy regarding when additional release is warranted. Inclusion of river management as a fluvial process not unlike previously considered natural events will allow for more accurate prediction of river adjustment and efficient river management in the future.

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CHAPTER III

EFFECTS OF URBANIZATION ON THE SIZE OF BEDLOAD SEDIMENT IN THREE LOW-GRADIENT RIVERS; POTENTIAL RAMIFICATIONS FOR BIOGEOMORPHOLOGY AND MORPHOLOGICAL STABILITY

3.1 Introduction

3.1.1 Sediment Size and Channel Stability

In assessment of morphological stability of river channels, sediment size is an important consideration for its influence on abiotic and biotic factors. In this study, channel stability is defined as the tendency of a river to migrate or to modify its channel at a rate consistent with rivers of similar type and in similar environments. Doyle et al. (2000) considers sediment size in assessment of channel stability, with fine sediment sizes correlating to high stability ratings and sand or loamy sand correlating to low stability ratings. Fine sediment is generally more cohesive than coarse, and so it follows that fine-grained channels will be more stable in natural rivers. Dams may make this standard less reliable by changing a high-flow river to low-flow. In this circumstance, coarse bed and/or bank sediment may remain in the channel although flow has been altered such that entrainment velocity is rarely, if ever, achieved. The presence of coarse sediment, then will imply a lower stability rating according to Doyle et al. (2000) even though the channel will rarely experience flow velocities sufficient to transport the sediment. One should not overlook, however, the role of coarse sediment in promoting channel stability, because coarse sediment encourages armoring (Lagasse et al., 1980). In this study, rivers are sandy with minimal gravel deposits, and so this is not expected to be a contributing factor.

Migration of a river channel is a function of stream power and sediment size (Nanson and Hickin, 1986), therefore, any influence which adjusts stream power or sediment size will alter the stability of the channel. In sand- and gravel-bed rivers, Nanson and Hickin (1986) found that basal sediment size was particularly influential in determining the rate of erosion. Hickin and Nanson (1984) found basal sediment size to be the most important variable reflecting bank erosion-resistance for sizes ranging from clay to large boulders. In the Hickin and Nanson (1984) study, lateral erosion declined to a minimum as grain size decreased from cobbles to very fine sand, then increased as sediment size further decreased to clay. For sandy rivers such as those in this study, it is then assumed that lower sediment sizes indicate more stable channels.

The rivers in the study area are generally low-velocity and, thus, bed and bank material is typically sand and silt-sized. Armoring was not prevalent in these channels, presumably because sediment sizes were not sufficiently coarse. The presence of sand to gravel layers in the channel indicate flashy, high discharge events, which are known to increase with urbanization (Bledsoe and Watson, 2000) and may increase the rate of channel adjustment. Typically, urbanization has caused an increase in sediment supply to rivers during the early stages of construction, followed by long-term decreases in sediment as a result of changes to land-cover (Bledsoe and Watson, 2000). Such an increase in bedload sediment will have far-reaching effects on channel morphology as buildup of coarse sediment reduces channel slope. Even after completion of construction, buildup of sediment in the bed of a river channel may continue if the channel is further modified by dams, weirs, or flow disruptors. The role of organisms as geomorphic drivers is also widely recognized, adding another dimension to the question of channel stability and sediment size. Fine sediment is attributed to lower water quality and increased suspended matter problematic for stream ecology. Both factors pose a threat of modification to biogeomorphic processes in the river channel.

In this study overviews are presented of the role sediment size has in abiotic geomorphic processes in river channels, the role of zoogeomorphology, and the impact of sediment size on organisms known to stabilize or destabilize river channels. Known stabilizing and destabilizing biota in the study areas are presented. Results of alluvium sampling upstream and downstream of major urban centers are presented, and the changes in sediment size and potential impact on geomorphology through abiotic and biotic processes discussed.

3.1.2 Role of Organisms in Geomorphic Processes

Sediment size directly influences water quality and ecological health, (Pauleit, 2005; Allen, 2015; Violin et al., 2016) which will in turn impact the populations of organisms exerting change on a river system. In a systems-approach to geomorphology, the role of organisms in geomorphological adjustment should therefore not be underestimated.

Biogeomorphology (Corenbilt et al., 2007, 2011; Viles, 1988, 2011; Steiger and Corenbilt, 2012), ecomorphology (Thoms and Parsons, 2002; Fisher et al., 2007; Wheaton et al., 2011), ecosystem engineering (Jones et al., 1994; Wright et al., 2006), microbial geomorphology (Viles 2000, 2012), and zoogeomorphology (Butler, 1995, 2018), have gained increased attention as important processes in landscape evolution (Davis, 1993; Meysman et al., 2006; Moore, 2006; Phillips, 2009; Reinhart et al., 2010; Jones, 2012; Albertson and Allen, 2015; Holtmeier, 2015; Phillips, 2015; Larsen et al., 2017; Butler, 2018; Polvi and Sarneel, 2018) and several special issues of academic journals have been devoted to the topic (James and Marcus, 2006; Renschler et al., 2007; Hession et al., 2010; Butler et al., 2012; Hupp et al., 2012; Coombs, 2016; Thoms et al., 2018). These are relevant topics in a consideration of sediment size because, as discussed herein, sediment size is related to water quality and habitat ecology, directly affecting the number and variety of organisms present, and also affects the type and degree of alteration. Although many aspects exist to zoogeomorphology and ecosystem engineering, I focus here on the lotic organisms most likely to be affected by water quality and sediment characteristics in the fluvial environment.

3.1.3 Biological Activity as Geomorphic Forcings

Organisms may be either stabilizers or destabilizers in the fluvial environment by their structures and activities, with equivalent levels of impact on the stability of the channel (Statzner, 2012; Albertson et al., 2014; Albertson and Allen, 2015; Cozzoli et al., 2019). Biofilms protect sediment from erosion by covering them with a smooth surface and decreasing the likelihood of entrainment (Polvi and Sarneel, 2018). Riparian plants stabilize stream banks and reduce the likelihood of bank collapse or mechanical erosion (Povi and Sarneel, 2018). Macrophytes are associated with increased bed stability, in some cases doubling the force needed to dislodge sediment (Fritz and Feminella, 2003; McBride et al., 2007; Liu et al., 2010; Polvi and Sarneel, 2018). Silk nets, constructed by caddisfly, midge and other insect larvae, have a similar effect (Edwards, 1962; Statzner et al., 1999; Cardinale et al., 2004; Statzner et al., 2005; Takao et al., 2006; Nunokowa et al., 2008; Johnson et al., 2009; Albertson et al., 2014, a & b). Studies cited in Statzner (2012) report increases of required force for sediment mobilization ranging from 23% (Johnson et al., 2009) to 1000% (Nunokawa et al., 2008) from the effects of silk spinning. This process is most effective on low-velocity environments with intermediate sediment sizes and channel stability (Cardinale, Gelmann, & Palmer, 2004; Nakano, Yamamoto, & Okino, 2005; Albertson and Allen, 2015). Studies of caddisfly larvae show that their role in consolidating bed sediment can double the critical shear stress required to entrain and transport sediment (Albertson et al., 2014a; Polvi and Sarneel, 2018) and that critical shear stress increases non-additively when multiple species compete for resources (Albertson et al., 2014b). Bioturbation is also observed, perhaps counter-intuitively, to stabilize channel sediment in some studies. Statzner et al. (1996) found that as *Dinocras* stonefly larvae remove fine sediment as they hunt prey, protection from surrounding bed material increases the momentum necessary to remove sand particles. Montgomery et al. (1996) studied the effects of spawning chum salmon and found that bed coarsening related to spawning activities increased critical shear stress from 33-54% of bank-full shear stress.

Rennie and Millar (2000) and Buxton et al. (2015b) likewise found the activities of spawning chum salmon act as stabilizing factors. Microorganisms have perhaps the greatest stabilizing effect in fluvial systems, as the presence of associated extracellular polymeric substances (EPS) increase critical shear stress of fine sediments by 500-3000% (Heinzelmann, 1992; Gerbersdorf et al., 2008, both cited in Statzner, 2012). The role of microorganisms in zoogeomorphology has long been neglected but is increasingly recognized as an important component (Viles, 2012).

In contrast, some fluvial organisms are destabilizers (Albertson and Allen, 2015). Feeding, burrowing, and tube-building by lotic organisms is observed to increase the rate of mixing fine sediment by 200%-750% (Mermillod-Blondin et al., 2002, 2004, cited in Statzner, 2012) whereas erosion of fine particles by mayflies and stoneflies ranges from 30% to 300% (Soluk and Craig, 1988, 1990; Wallace et al., 1993; Statzner et al., 1996; Zanetell and Peckarsky, 1996; Parkyn et al., 1997). Tadpoles can decrease fine bed sediment by 30-80% through bioturbation and feeding (Power, 1990; Ranvestel et al., 2004) whereas freshwater shrimp decrease inorganic epibenthic sediment mass by up to .03 kg/m^2 per day (Pringle and Blake, 1994; March et al., 2002; Cross et al., 2008). Fish mobilize and erode sediment by digging redds (Hildebrand, 1971; Field-Dogsdon, 1987; Kondolf et al., 1993; DeVries, 1997, 2012; Montgomery et al., 1996; Rennie and Millar, 2000; Gottesfield et al., 2004; Hassan et al., 2008, 2015; Buxton et al., 2015a & b), feeding (Flecker, 1996, 1997; Statzner et al., 2003b; Flecker and Taylor, 2004; Statzner and Sagnes, 2008; Pledger et al. 2014, 2016, 2017; Canal et al., 2015; Pledger, 2015; Rice et al., 2019), spawning (Fremier et al., 2018) and bioturbation (Power, 1990; Gottesfield et al., 2008; Shirakawa et al., 2013). In gravel-bed rivers, fish effectively disrupt sediment and lower the velocity of sediment entrainment by foraging activities (Pleger et al., 2017). In Statzner et al. (2003b), the digging activities of gudgeon decreased critical shear stress of sand by up to 60% and gravel by up to 35%. Crayfish are also widely studied destabilizers. In the United Kingdom, a crayfish infestation induced sediment entrainment through bioturbation including construction and maintenance of burrows, foraging for food on the riverbed and fighting with or maneuvering away from other crayfish during resource conflicts (Rice et al., 2016). Such activities added at least 47% more suspended sediment to the base flow of the rivers (Rice et al., 2016). In crayfish-impacted areas, the critical shear stress required to move sediment can decrease by 75%, resulting in a greater transport of fine sediment (Parkyn et al., 1997; Statzner et al., 2000; Statzner et al., 2003a; Creed and Reed, 2004; Usio and Townsend, 2004; Zhang et al., 2004; Helms and Creed, 2005; Statzner and Peltret, 2006; Statzner and Sagnes, 2008; Ludlam and Magoulick, 2009; Johnson et al., 2011; Rice et al., 2012; Statzner, 2012; Harvey et al. 2011, 2014; Faller et al., 2016; Polvi and Sarneel, 2018). Still other organisms are stabilizers and destabilizers. Zimmerman and de Szalay (2007) found that unionoid mussels exerted both effects alternatively as they established themselves in streambed environments.

3.1.4 Effects of Fluvial Characteristics on Efficiency of Biogeomorphological Processes

The stability of bed sediment in an aquatic environment is dependent on the balance between hydrodynamic forces that cause erosion and the forces within the sediment that resist it (Grabowski et al., 2011). Therefore, forces which disrupt either populations of stabilizers or destabilizers disrupt erodibility of the channel material and in turn, stability of the channel.

Sediment size may have a direct effect on the activity of stabilizers and destabilizers. For example, Arnon et al. (2009) found that the stabilizing effects of particle retention by biofilms increase with particle size. Indirect effects center on water quality and ecological alteration which impact the lotic populations present. Water quality is directly connected to sediment size (Salomons, 1985; Albertson and Allen, 2015). Adsorption of micro-pollutants on suspended sediment and subsequent sedimentation removes pollutants from the water column, but deposits them in the bed load, where they will affect benthic organisms (Salomons, 1985; Yujun et al., 2008). Pollution, including trace metals, is more readily adsorbed by fine sediment, making high levels of fine suspended sediment an indicator of low water quality (Salomons, 1985; Mohiuddin et al., 2009; Albertson and Allen, 2015). Levels of fine suspended sediment also affect fish habitat and negatively alter the fluvial ecosystem (Pauleit, 2005; Violin et al., 2016).

According to Moore (2006), the degree of impact organisms will have on the environment depends on the behavior, body size, and population density of the organisms. These factors are mediated, in turn, by abiotic factors of the ecosystem such as sediment size. As the ecosystem is adversely impacted by heightened levels of fine sediment, one can consider sediment size relevant to channel stability for its direct effect on bank erodibility and its effect on organisms which influence sediment erodibility. An untested yet pervasive assumption is that the impact of animals on sediment flux is minor relative to geophysical forcing, causing sediment transport to be regarded as a mainly abiotic process (Phillips, 2009; Rice et al., 2016). Few measurements of the suspended sediment flux caused by bioturbation in rivers exist, however, nor any evaluation comparing its magnitude to the effects of hydraulic processes (e.g. Rice et al., 2016). The effects of marine bioturbation have been studied more than those in the fluvial realm, and most of these studies focus on ecological questions rather than geomorphic (Rice et al., 2016). Some studies (Reinhart et al., 2010; Polvi and Sarneel, 2018) imply important feedback between organisms and fluvial processes. Sediment size may play an important role in susceptibility to biotic influence; rivers with lower discharges and smaller grain sizes seem to be more heavily impacted by biotic factors, whereas those with higher discharges and larger grain sizes are dominated by physical forces, not biological (Moore, 2006; Albertson and Allen, 2015; Polvi and Sarneel, 2018). Because the rivers in this study are low-gradient and generally low-velocity, it can be assumed that biotic factors will play a prominent role in the entrainment and transport of sediments.

3.1.5 Stabilizers and Destabilizers in the Study Areas

Tables 1 and 2 present biogeomorphologically important biota of the study area. These tables do not represent all lotic biota present, but those playing the greatest role on geomorphic processes and are most likely to be affected by changes in sediment size.

Table 6: Vertebrate Biota of the Rivers in the Study Area

River	Organism	Stabilizer	Destabilizer	Method	References
Trinity	Bowfin	X	X	Predation of destabilizers; nesting	Haussman, 1998; Texas Parks & Wildlife, 2020c
Brazos, Trinity	Black Bullhead		X	Hibernation	Dehring and Krueger, 2008; Texas Parks & Wildlife, 2020a, c
Brazos, Colorado, Trinity	Centrarchidae (Bass, Redbreast Sunfish, Bluegill, Crappie, Warmouth)		X	Nest excavation	Martin, 2013; Texas Parks & Wildlife, 2020a, b, c
Colorado	Cichlid, Rio Grande		X	Nest excavation, burrows	Ribbink et al., 1981; Texas Parks & Wildlife, 2020b
Brazos, Colorado, Trinity	Cyprinoformes (Minnows, Chub, Carp, Carpsuckers, Smallmouth buffalo, Redhorse, Smalleye and Sharpnose Shiner)		X	Feeding, foraging	Texas Master Naturalist Program, 2012; Pledger et al., 2014; Huser et al., 2016; Rice et al., 2019; Gooch et al., 2012; Texas Parks & Wildlife, 2020a, b, c
Colorado	Eel, American		X	Burrowing	Texas Parks & Wildlife, 2020b
Brazos, Colorado, Trinity	Freshwater Drum	X		Predation on destabilizers	Griswold and Tubb, 1977; Texas Parks & Wildlife, 2020a, b, c

Table 6: Vertebrate Biota of the Rivers in the Study Area, cont'd.

River	Organism	Stabilizer	Destabilizer	Method	References
Brazos, Colorado, Trinity	Alligator Gar	X		Predation on destabilizers	Kennedy and Mondragon, ed 2013; Texas Parks & Wildlife, 2020a, b, c
Trinity	Herring, Skipjack	X	X	Predation on destabilizers and stabilizers	Chandler, 2014; Texas Parks & Wildlife, 2020c
Brazos, Colorado, Trinity	Ictalarus (Catfish - blue, channel, and flathead)		X	Burrowing	Harvey et al., 2019; Texas Parks & Wildlife, 2020a, b, c
Trinity	Needlefish, Atlantic	X	X	Predation on destabilizers and stabilizers	Arceo-Carranzaet al., 2004; Texas Parks & Wildlife, 2020c
Trinity	Pacu, Redbelly		X	Consumption of lotic vegetation	Texas Parks & Wildlife, 2020c
Brazos, Colorado, Trinity	Slender Gar (Spotted and Longnose)	X		Predation on destabilizers	Kennedy and Mondragon, 2013; Texas Parks & Wildlife, 2020a, b, c
Brazos	Gizzard Shad		X	Feeding activities; bioturbation	Shepherd and Mills, 1996; Schaus, 2007; Texas Parks & Wildlife, 2020a
Brazos, Trinity	Rainbow Trout		X	Digging redds	DeVries, 2012; Texas Parks & Wildlife, 2020a, c

Table 7: Invertebrate Biota of Rivers in the Study Area

River	Organism	Stabilizer	Destabilizer	Neutral	Method	References
Brazos, Colorad o, Trinity	Crayfish		X		Burrowin g, bioturbati on	Telfair, 1981; Rice et al., 2016; U.S. Fish & Wildlife Service, 2017
Brazos, Colorado, Trinity	Mayflies, Caddisflies	X			Net-spinning	Albertson et al., 2014a; Polvi and Sarneel, 2018; Cloud, 1973; Johnson & Kennedy, 2003; Diaz et al.,
Brazos, Trinity	Mussels (various species)	X	X		Embedding, burrowing	Zimmerman and de Szalay, 2007; Lash, 2011 Slye et al., 2011; Gooch et al., 2012
Brazos, Trinity	Oligochaete and Tubificinae (various burrowing worms)		X		Burrowing	Lash, 2011; Slye et al., 2011

Biota of the rivers in the study area impose varying levels of modification on the river channel, and roles as stabilizers or destabilizers are often difficult to distinguish. Bowfin, for example, act as destabilizers through nesting, but the role as predators of crayfish

(Hausmann, 1998), gives the presence of bowfin a stabilizing force in river channels.

Drum likewise cause only minor direct destabilization, because they neither create nests nor forage for food, but indirectly produce stabilizing effects by their diets. During adulthood, its primary food sources are the destabilizing shad, crayfish, and molluscs (Griswold and Tubb, 1977). Skipjack herring and Atlantic needlenose pose little direct alteration to a river channel through spawning or feeding activities, but indirectly influence biogeomorphology through their diets by consuming destabilizers and stabilizers (Arceo-Carranzaet al., 2004; Chandler, 2014).

Gar consistently stabilize channels. Alligator gar elicit only minor destabilizing effect on channel substrate, because they spawn in flooded vegetation rather than the main river channel and produce a greater stabilizing effect by preying on destabilizing foragers (Kennedy and Mondragon, 2013). Likewise, the effects of net-spinning by caddisflies and mayflies have a stabilizing effect on channel substrate (Soluk and Craig, 1988, 1990; Wallace et al., 1993; Statzner et al., 1996; Zanetell and Peckarsky, 1996; Parkyn et al., 1997). Other local biota are consistent destabilizers. Bullhead catfish regularly burrow into shorelines with only their mouths and gills exposed above the mud (Dehring and Krueger, 2008). Cichlidae destabilize sediment by excavating nests and burrows (Ribbink et al., 1981, cited in Muñiz et al., 2015). Centrarchidae such as bass, sunfish, bluegill, crappie and warmouth disrupt sediment by excavating bowl-shaped nests (Martin, 2013, cited in Muñiz et al., 2015). The American eel, found in parts of the Colorado River, burrows into substrate to escape extreme heat and cold, both of which are prevalent in central Texas (Tomie et al., 2015). The non-native redbelly pacu have been found in Texas waterways during recent years, likely as aquarium releases (Howells, 1992). Though not thought to overwinter or spawn in Texas, during their lifetimes they exert a destabilizing force on waterways by consuming lotic vegetation. Shad can disrupt entire ecosystems through their feeding activities and destabilizing river channels through bioturbation and high rates of consumption (Shepard and Mills, 1996; Schaus, 2007).

3.2 Study Location

3.2.1 Brazos River at Waco, Texas

The Brazos River extends 1,352 km from the confluence of its Salt Fork and Double Mountain Fork in Stonewall County to its mouth in the Gulf of Mexico near Freeport in Brazoria County (Hendrickson, 2019) (Figure 21).

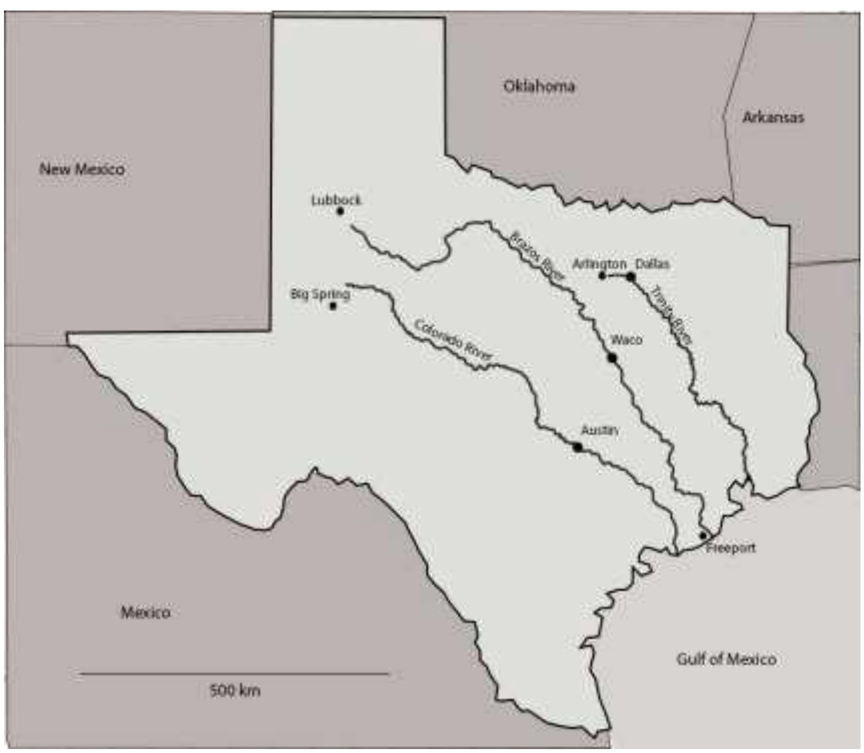

Figure 21: Location of rivers in this study.

The longest river in Texas, the Brazos River has the highest average annual discharge of any Texas river at 7.4 km^3/s (Texas State Historical Association, 2018; Hendrickson, 2019). This study examines a ~27 km reach beginning ~12 km upstream of the city of Waco and extending ~11 km downstream of Waco (Figure 22). Waco has an estimated population of 268,696 as of 2017 (United States Census Bureau, 2018), and the Brazos River flows directly through the city. Near Waco, the Brazos River flows through Cretaceous-aged Austin Chalk, the Wolfe-City Formation, and the Ozan formation. These units exhibit interbedded limestone, marl, sandstone, and clay.

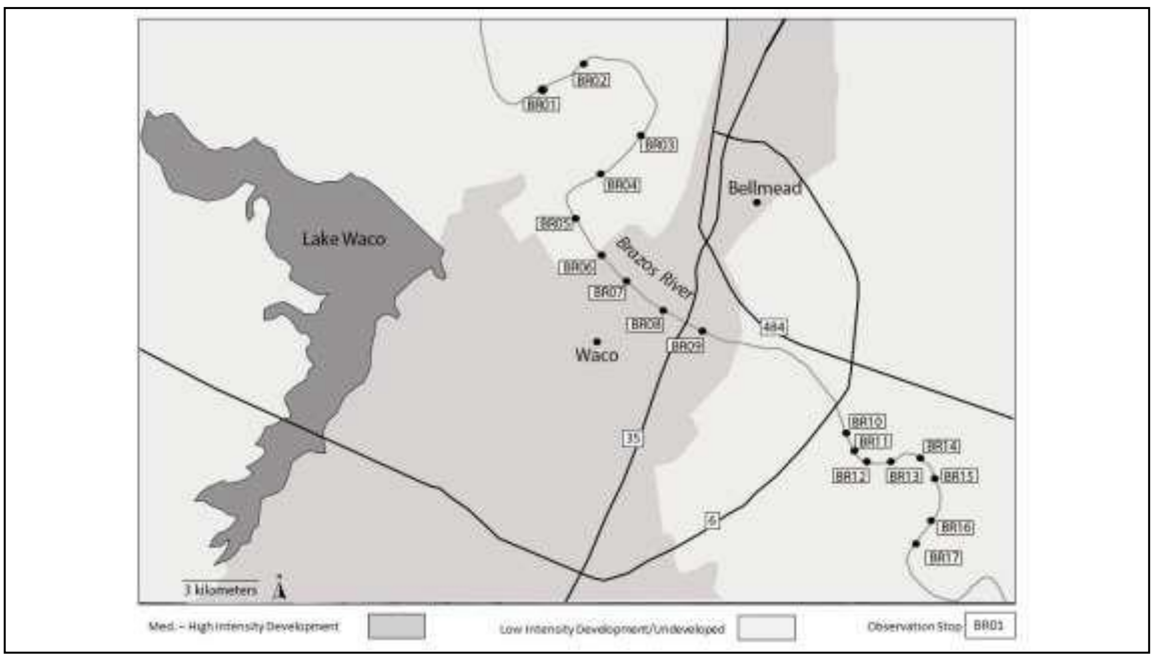

Figure 22: Observation stops on the Brazos River near Waco, Texas

The Brazos River was assessed for stream power on July 5 and 6 of 2019. Gage height on these dates ranged from 3.0-6.0 ft (.9-1.8 m) and discharge ranged from 1,000 to ~4,000 ft^3/s (28-113 m^3/s). The river was not observed during bankfull flows for safety considerations. An attempt was made to observe the river at flows which approximate average. Waco received 7.38 inches (18.75 cm) of precipitation during the month of June 2019.

This reach of the Brazos River flows through a modified stretch in Waco where the channel has been often reinforced with stone or wood and vegetation cleared (Figure 23).

Figure 23: Modified river banks in Waco, Texas

Upstream of Waco, the river flows through natural alluvium or limestone bedrock channels (Figure 24).

Figure 24: Brazos River channel upstream of Waco, Texas.

Immediately downstream of the most urbanized reach, a labyrinth weir manages water levels for flood control and creates a region locally known as Lake Brazos

This should not be confused with the nearby Lake Waco Dam, which crosses the Bosque River. The Bosque River is a tributary to the Brazos River, joining at a confluence just north of Waco. The Brazos River Authority does not release water from dams in anticipation of excess precipitation, but in response to upstream and in-city gage readings (Brazos River Authority, 2019). Upstream put-in and take-out was at Brazos Park East. River flow levels allowed paddling downstream and upstream with considerable effort; thus, no separate take-out was used. Downstream of Waco, put-in and take-out was near the Hwy-6 overpass, where flow levels again allowed for returning by paddling upstream with effort (Figure 25).

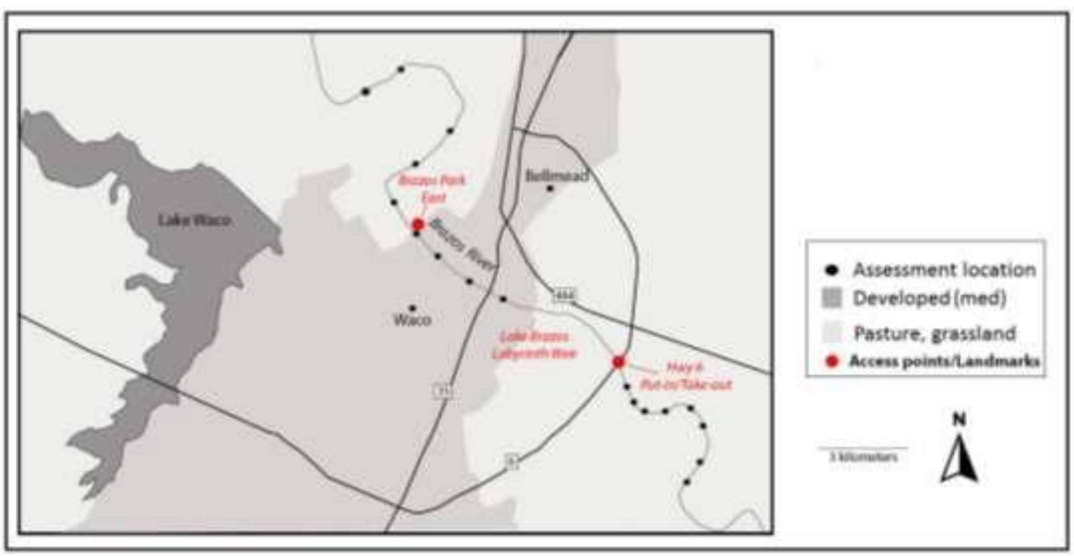

Figure 25: Access points and landmarks on the Brazos River near Waco, Texas.

3.2.2 Colorado River at Austin, Texas

The Colorado River extends 1,387 km from its headwaters near Lubbock, Texas, to the Gulf of Mexico and has a total drainage area of 103,341 km2 (Kammerer, 1987). This study assesses the river in the vicinity of Austin, Texas. Austin has a population of 950,715 as of 2017 (United States Census Bureau). The Colorado River in the observed reaches cuts through the Cretaceous-aged Upper Glen Rose Limestone (limestone, dolomite, and marl), the Fredericksburg Group (limestone, dolomite, and chert), and Austin Chalk. Channel slope in the study reaches is ~.0006. Average annual discharge of the Colorado River is 2.34 km^3/s (Texas State Historical Association, 2018) (Figure 21).

Urban sprawl associated with Austin extends significantly to the northwest, following the Colorado River upstream. For this reason, observations of the river in a natural state upstream of Austin urbanization and suburbanization had to occur near Smithwick, Texas, approximately 50 miles (80.5 km) northwest of Austin (Figure 26).

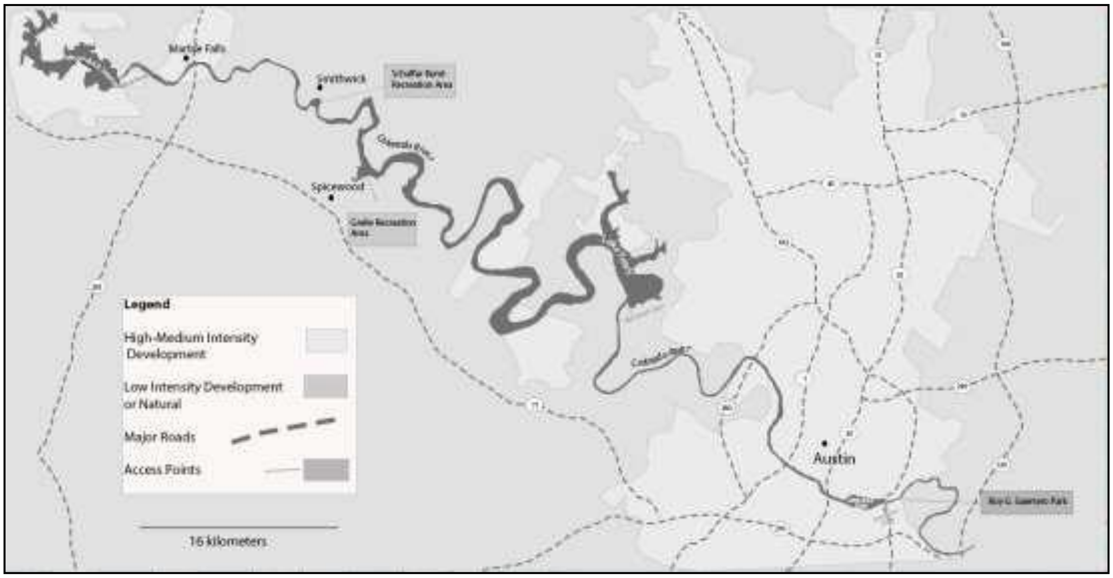

Figure 26: Access points on the Colorado River near Austin, Texas

Despite the distance, the Colorado River in Smithwick flows through the same geology and climate as in Austin, and thus, allows for comparison of channel morphology before the effects of urbanization. Put-in for the upstream reach was at the Shaffer Bend Recreational Area, managed by the Lower Colorado River Authority (LCRA) and take-out was at the Grelle Recreational Area, also managed by the LCRA.

The Colorado River was assessed during June 6-8, and June 14-15, 2019. Gage height ranged from 4,000 to ~4,500 ft^3/s (113-127 m^3/s) during June 6-8 and 1,500-3,000 ft^3/s (42.5-85 m^3/s) during June 14-15. Discharge on June 6-8 averaged 16.17-16.75 ft. (~5 m) and on June 14-15 averaged 12.5-15.5 ft (3.8-4.7 m). Bankfull discharge was avoided for safety considerations, and to take measurements which approximated the average flow of the river. Austin received 7.52 inches (19.1 cm) of rain in May 2019.

Two dams affect the Colorado River near Austin. Mansfield Dam creates Lake Travis, about 30 km upstream of Austin, and Longhorn Dam creates Lady Bird Lake in the Austin city limits. The river flows for approximately 43 km between the two dams, through heavily suburbanized and urbanized channel reaches. The suburban reaches have been continuously stabilized using wood or stone, and flow through alluvium or limestone bedrock channels. Interestingly, much of the urban reaches exhibit less stabilization, though wood and concrete stabilization does exist in some areas. Access to the river in Austin is readily available at the I-35 overpass or farther upstream at Rowing Dock, a canoe and paddle board rental business. Flow is slow enough that paddling downstream and upstream is possible, thus, no separate take-out location is necessary.

Sediment from the Colorado River was collected downstream of Austin beginning at the Roy G. Guerrero Park near Longhorn Dam. Access here is a favorite for kayakers, though accessing the river with a canoe is a challenge. Take-out was the FM-973 overpass (Figure 27).

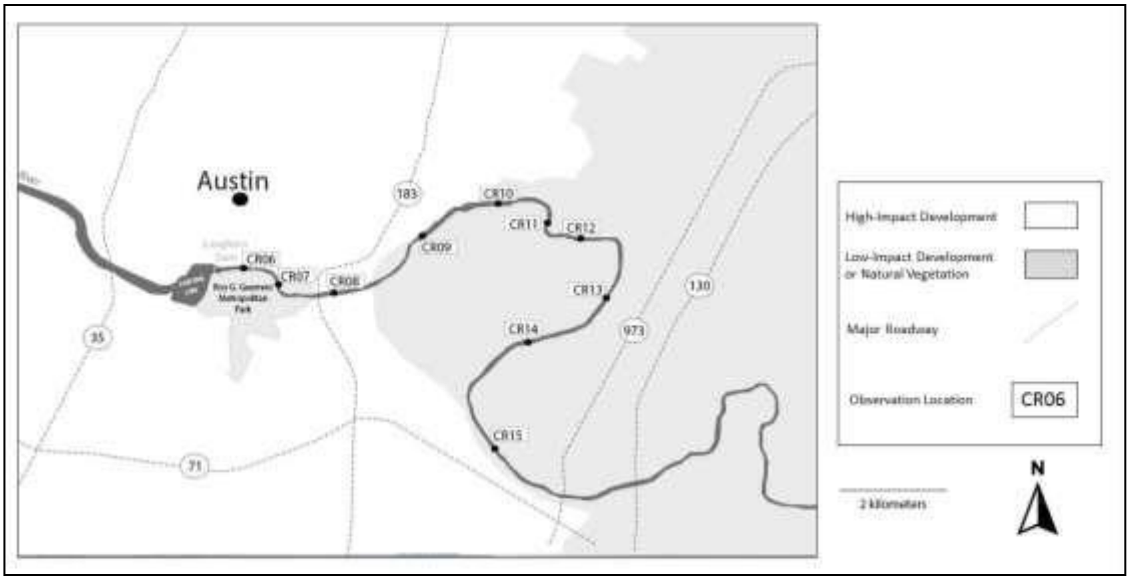

Figure 27: Access points on the lower Colorado River near Austin, Texas

Downstream of Austin, the Colorado River flows through a natural channel with undeveloped banks. Two locations in the study area create flow disruptions: a weir precariously placed beneath the US-183 overpass such that it does not appear on aerial photographs and surprises unsuspecting canoeists, and a recreational standing wave at a southward bend of the channel 10 km downstream of Longhorn Dam. Future researchers are advised to consult aerial photographs before canoeing this reach, because the placement of the standing wave on a bend causes it to be out of sight until one is directly upon it.

3.2.3 Trinity River at Dallas, Texas

The Trinity River originates at the confluence of West and Elm Forks northwest of Dallas, Texas and east of Arlington, Texas. It extends 1,142 km to its mouth at Trinity

Bay in Chambers County, Texas. (Figure 28). Average annual discharge is 7.03 km^3/s. In this study area, the Trinity River originates in Cretaceous-aged limestone, shale and sandstone of the Eagle Ford Group before flowing southwest through the Austin Chalk, lower Taylor marl, and calcareous silt and sand of the Neylandville and Marlbrook Marl formations, both Taylor group.

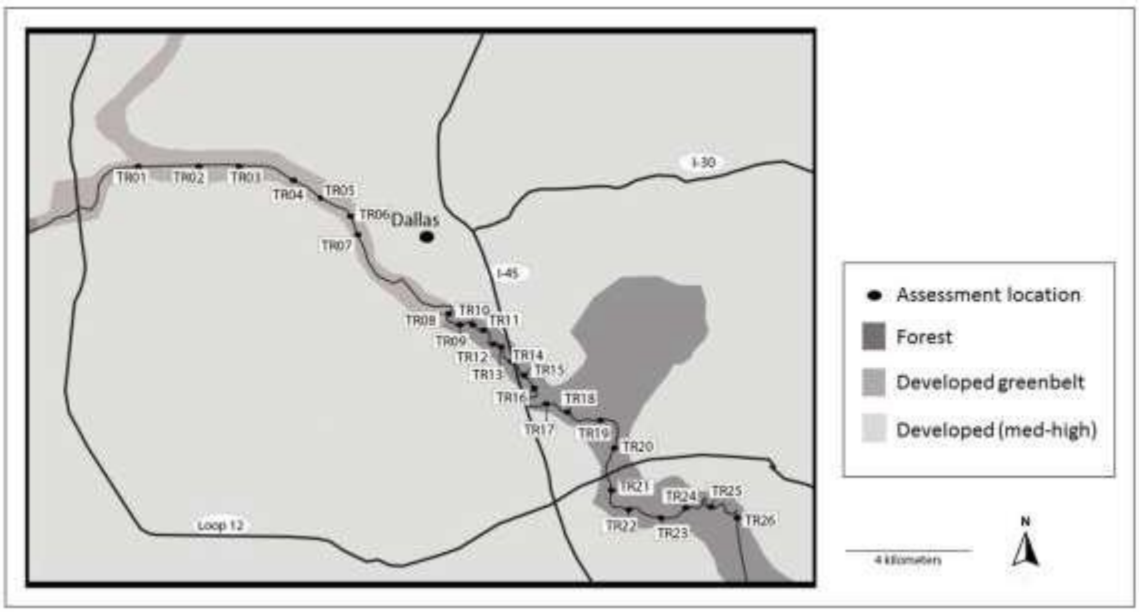

Figure 28: Observation locations on the Trinity River near Dallas, Texas

Collection sites begin at the confluence of the West Fork and Elm Fork, marking the origin of the Trinity River main channel. Although this reach is geographically within an urbanized region of the Dallas-Fort Worth-Arlington metroplex, the channel is unaltered by engineering structures and retains a wide greenbelt on either bank extending nearly half a kilometer on each side of the river. As the river turns southwest through the city of

Dallas, the greenbelt ceases to exist, and the channel is reinforced with concrete. At the Santa Fe railroad trestle, channelization ends as the river flows into the protected Great Trinity Forest and continues as a natural channel.

No dams are present on this stretch of the Trinity, although a constructed standing wave was emplaced at the Santa Fe railroad trestle. Though present for the first field excursion in May of 2018, this was removed during June-November 2018.

3.3 Methodology

Bed sediment was collected at each location from a depth of 1.5-2 ft (45-60 cm) using post-hole diggers and stored in gallon-sized plastic zip bags. Sediment was placed in a drying oven at 80^{o}C until fully dried, at least 30 minutes, and then sieved for 20 minutes using mesh sizes 2-4.76 mm, 850 um-2 mm, 425-850 um, 250-425 um, 125-250 um, and 75-125 um.

3.4 Results

3.4.1 Brazos River

The percentage of sediment in each size range from each collection site on the Brazos River is presented in Table 8.

	Medium Sand	Fine Sand	Very Fine Sand	Silt
	250-425 um	125-250 um	75-125 um	<75 um
Stop 1	0.211009	0.46789	0.220183	0.100917
Stop 2	0.061905	0.495238	0.442857	0
Stop 3	0.040921	0.55243	0.199488	0.207161
Stop 4	0.093923	0.309392	0.325967	0.270718
Stop 5	0.313433	0.487562	0.134328	0.064677
Stop 6	0.060071	0.416961	0.310954	0.212014
Stop 7	0.07971	0.336957	0.300725	0.282609
Stop 8	0.11828	0.567204	0.196237	0.11828
Stop 9	0	0.551724	0.298851	0.149425
Stop 10	0.16	0.28	0.26	0.3

Table 8: Percentage of sediment in each size range from collection points on the Brazos River, Texas. Stops progress numerically from upstream of Waco (Stops 1-5) to downstream of Waco (Stops 6-10).

As a percentage of overall sample size, silt increased from 10% to 30% from upstream of Waco to the final stop farthest downstream of Waco (Figure 4).

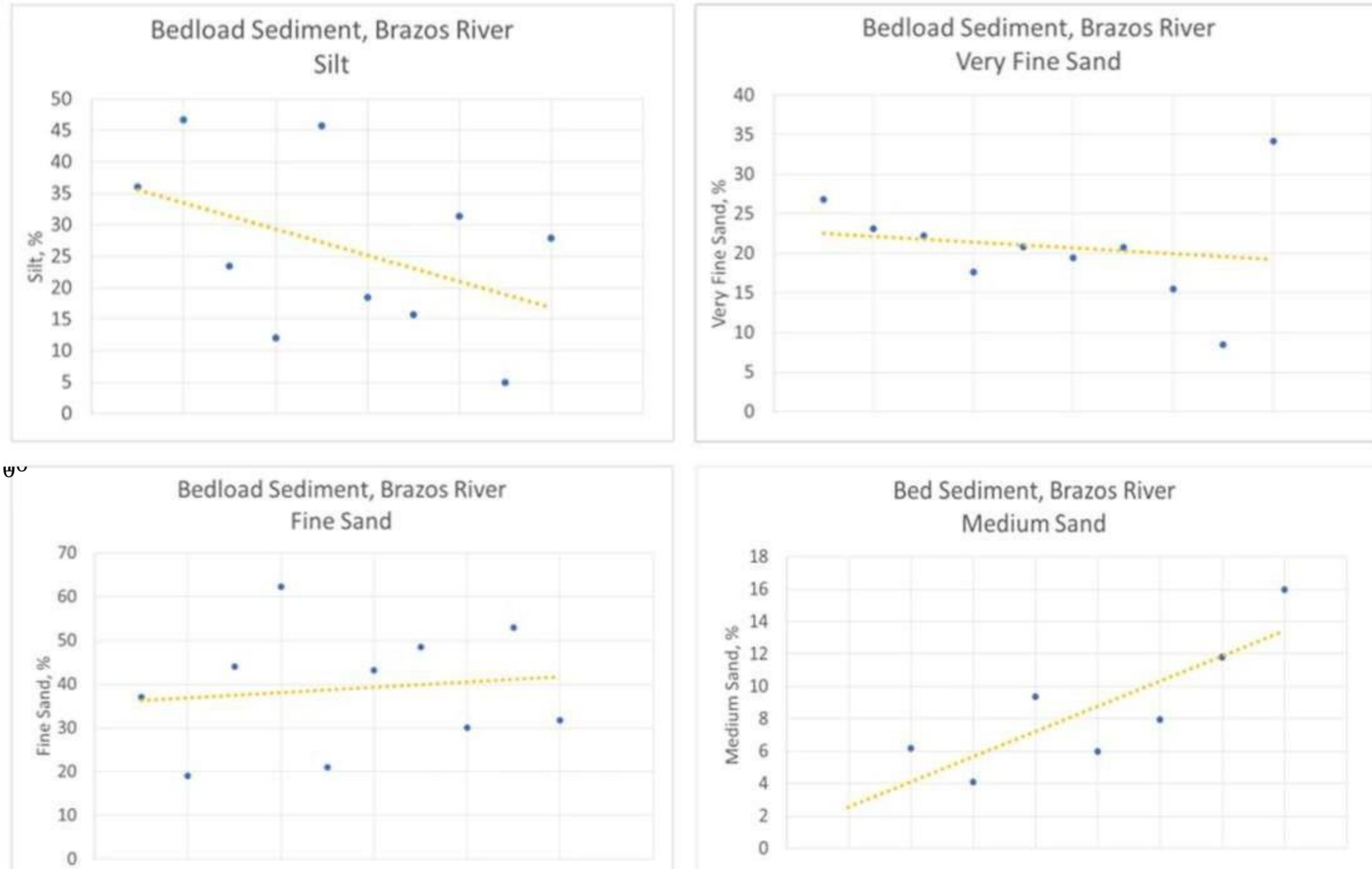

Figure 4: Relative percentages of grain sizes from upstream (left side of graph) to downstream (right side of graph) of Waco, Texas on the Brazos River

Very fine sand decreased from 27% to 9% (one outlier removed) and fine sand component decreased from 47% to 28%. Medium-sized sand decreased from 21% to 16%. Overall, the average maximum size of sediment in the Brazos River decreased from 242 um to 193 um (Figure 5).

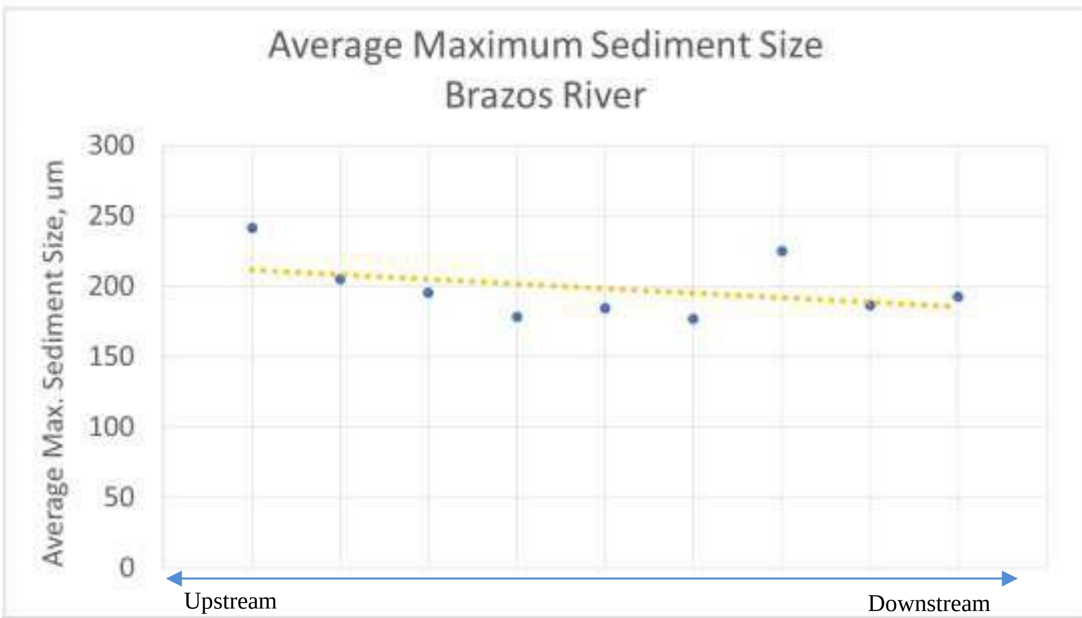

Figure 5: Average maximum sediment size at stops upstream and downstream of Waco, Texas on the Brazos River.

3.4.2 Colorado River

The percentage of sediment in each size range from each collection site on the Colorado River is presented in Table 9.

	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt
	> 425 um	250-425 um	125-250 um	75-125 um	<75 um
Stop 1	0.3370	0.2482	0.2667	0.0888	0.0593
Stop 2	0.3097	0.3784	0.1384	0.1458	0.0277
Stop 3	0.0000	0.2739	0.5389	0.1174	0.0698
Stop 4	0.0000	0.1215	0.2829	0.2163	0.3792
Stop 5	0.0395	0.4563	0.3866	0.0576	0.0600
Stop 6	0.0000	0.2205	0.5590	0.2205	0.0000
Stop 7	0.0000	0.1312	0.1674	0.3032	0.0000
Stop 8	0.3217	0.1565	0.1739	0.3478	0.0000
Stop 9	0.0000	0.1667	0.2826	0.1884	0.3623
Stop 10	0.0000	0.2443	0.7557	0.0000	0.0000
Stop 11	0.0000	0.2495	0.5471	0.2033	0.0000
Stop 12	0.1111	0.0933	0.3911	0.4044	0.0000

Table 9: Percentages of various sediment sizes in the Colorado River near Austin, Texas. Stops progress numerically from upstream of Austin (Stops 1-6) to downstream of Austin (Stops 7-12).

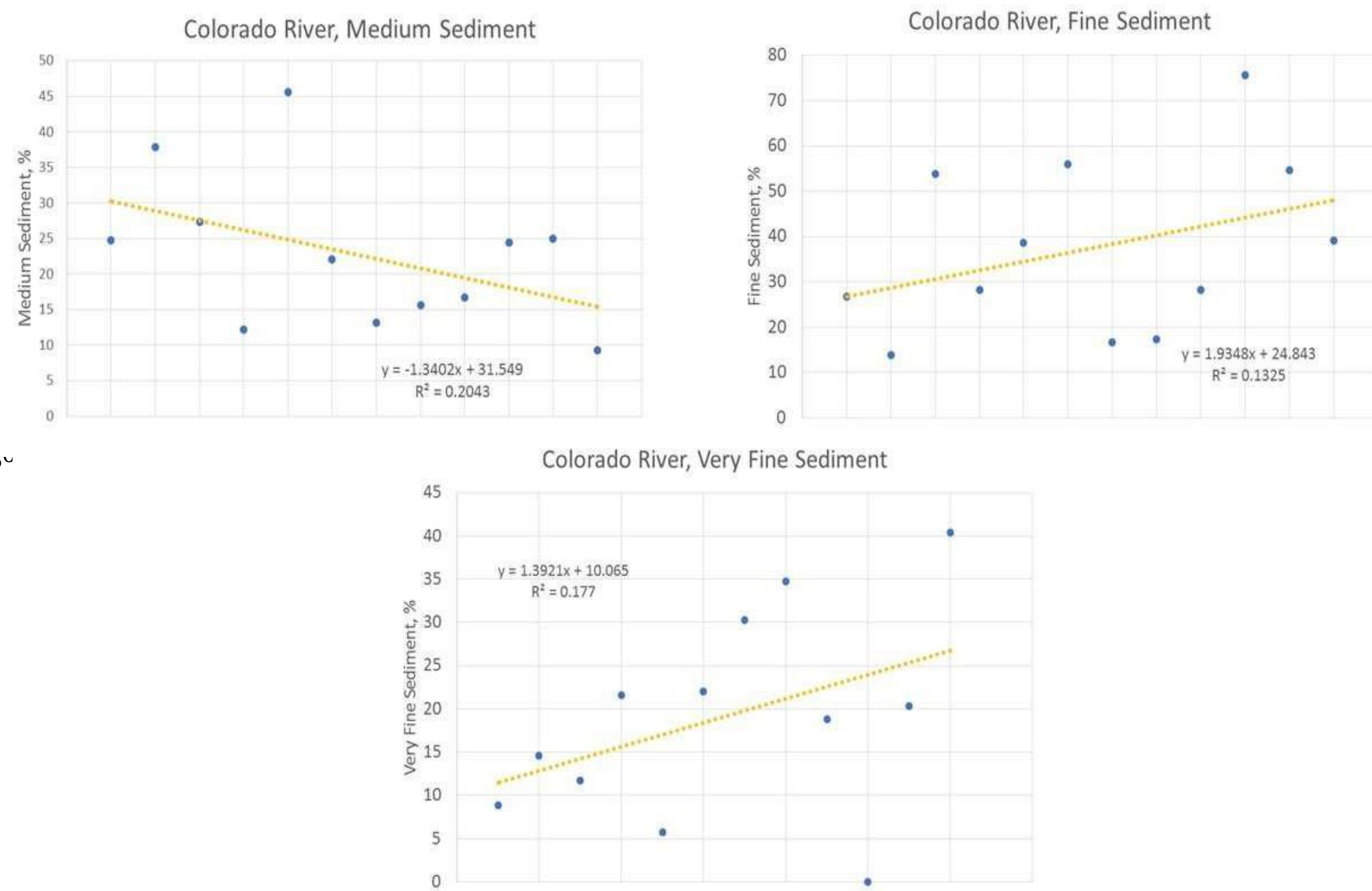

Figure 6: Changes in abundances of various sediment sizes, Colorado River near Austin, Texas

Average bed sediment size was calculated for each observation stop. These results are presented in Figure 7.

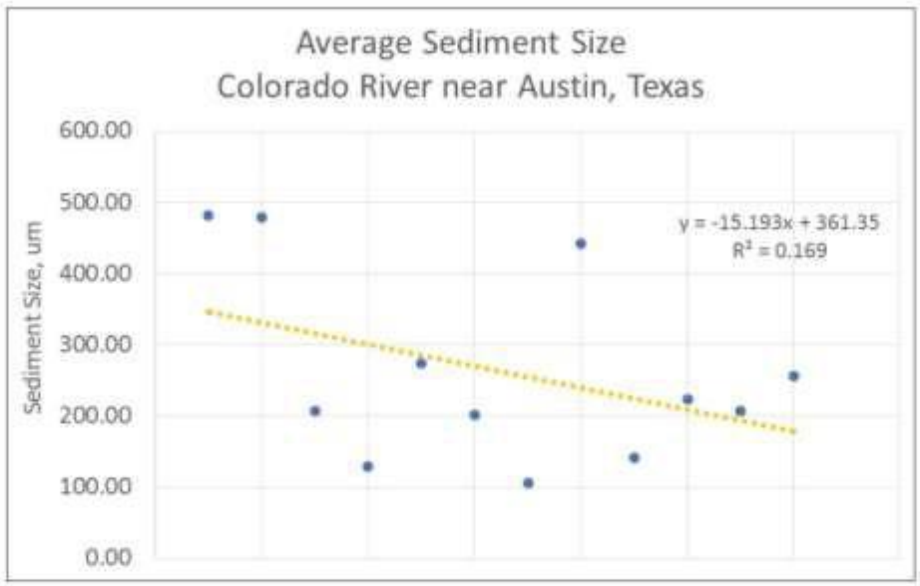

Figure 7: Average sediment size at each stop on the Colorado River near Austin, Texas.

3.4.3 Trinity River

The percentage of sediment of each size range from each collection site on the Trinity River is presented in Table 10.

	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt
	425-850 um	250-425 um	125-250 um	75-125 um	<75 um
Stop 1	0	0	0.371244033	0.26797248	0.360783
Stop 2	0	0.110821657	0.190734352	0.231289164	0.467155
Stop 3	0	0.102087939	0.440874478	0.22235323	0.234684
Stop 4	0	0.08048898	0.622354642	0.176444814	0.120712
Stop 5	0	0.122616373	0.210908521	0.208400815	0.458074
Stop 6	0.093819778	0.095598532	0.431745071	0.194224728	0.184612
Stop 7	0.070646766	0.079819652	0.484514925	0.207835821	0.157183
Stop 8	0	0.228970126	0.301493711	0.155070755	0.314465
Stop 9	0.042033314	0.292672425	0.53007185	0.085223756	0.049999
Stop 10	0	0.061753174	0.317261016	0.342279686	0.278706

Table 10: Weighted average of sediment sizes from collection points on the Trinity River, Texas. Stops progress numerically from upstream (Stops 1-5) to downstream (Stops 6-10) of Dallas.

As a percentage of overall sample size, silt decreased from 47% to 28% (Figure 8). Very fine sand decreased from 27% to 9% and fine sand increased from 37% to 53%. Medium-sized sand remained fairly constant at a value of 6-11% of total, with the exception of two outliers downstream of Dallas, where medium sand spiked to 23% and 29% of total sample. Overall, the maximum sediment size in the Trinity River increased from 153-271 um (Figure 9), representing a change from fine sand to medium sand.

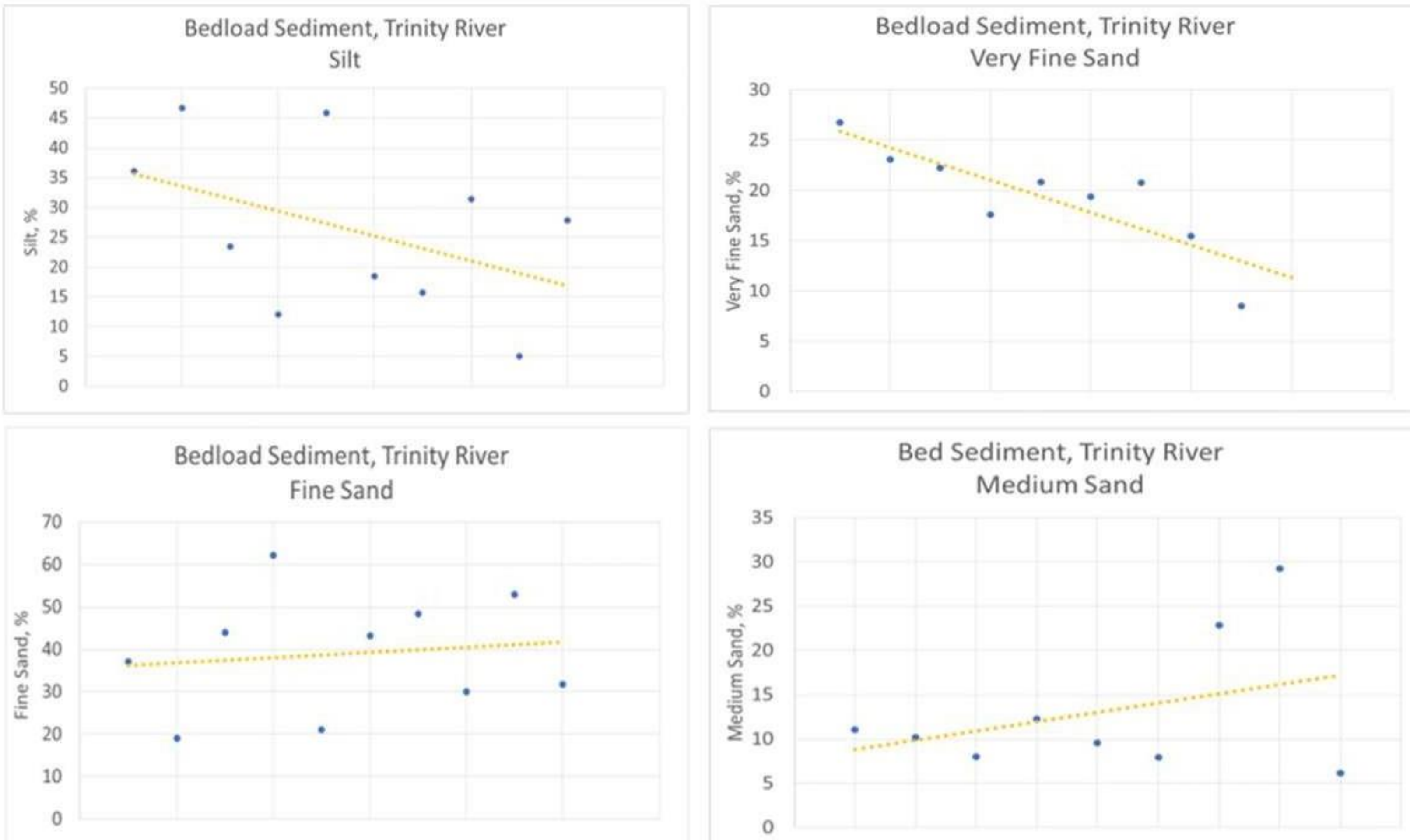

Figure 8: Relative percentages of grain sizes from upstream (left side of graph) to downstream (right side of graph) of Dallas, Texas on the Trinity River

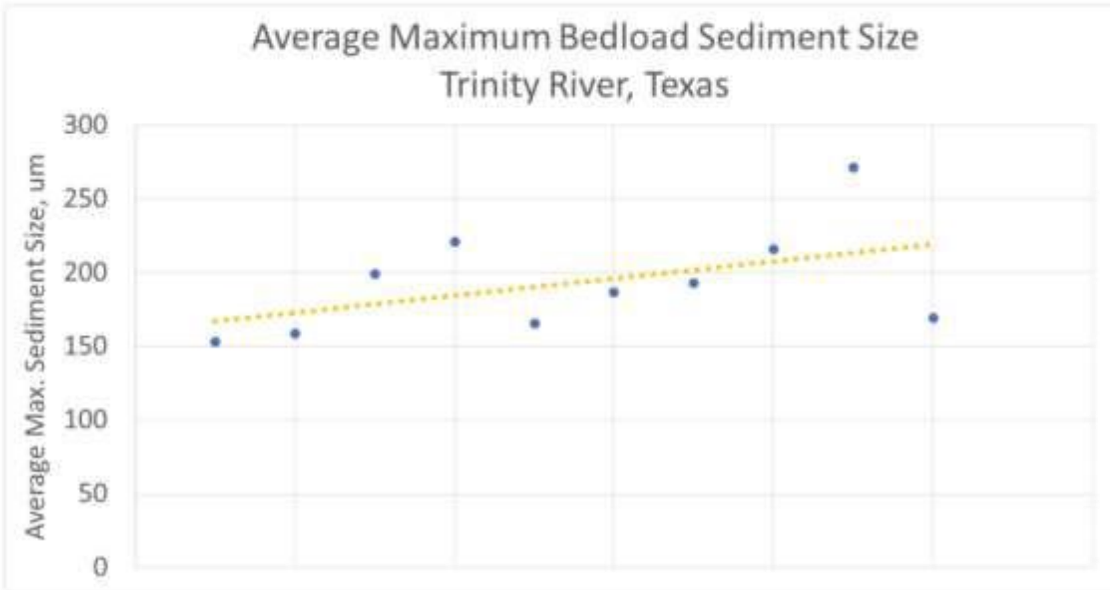

Figure 9: Average maximum sediment size at stops upstream and downstream of Dallas, Texas on the Trinity River.

3.4 Discussion

This study attempts to discern the impacts of urbanization on sediment size for the purpose of identifying potential threats to morphological stability of the channel. Sediment size plays a direct role in the migration of the channel by its influence on armoring and velocity of entrainment flow, and an indirect role by its influence on biogeomorphological processes. A discussion of these two forces is now presented.

3.4.1 Role of Sediment Size in Channel Stability

Any influence which adjusts stream power or sediment size will alter the stability of the channel. Table 11 presents average values for stream power and unit stream power for the same river reaches sampled in this study. These data were collected in the field during the summer of 2019.

	Colorado River, Ω	Colorado River, ω	Brazos River, Ω	Brazos River, ω	Trinity River, Ω	Trinity River, ω
Upstream	163344.028	512.136	3142.91	24.22	159.434	4.37
Within	127356.582	670.298	6069.12	46.69	75.9	2.98
Downstream	31036.536	186.521	1855.21	21.28	1284.6	15.46

Table 11: Average stream power and unit stream power for reaches of the Brazos, Colorado, and Trinity Rivers, Texas

In the Brazos River, the decrease in stream power coincides with the reduction in sediment size observed in this study. The Trinity River exhibits an increase in stream power downstream of Dallas, coinciding with an increase in sediment size as observed in this study. That stream power values should exhibit positive correlation with sediment size supports our initial hypothesis. The potential implications for channel stability should also not be considered solely on these data. Many factors contribute to stability of the channel such as type of channel modification, level of watershed modification, and management practices. These factors are addressed in other chapters of this dissertation, and a full discussion is presented in its conclusion. Maintaining a focus on sediment size for this discussion, however, changes to sediment size on the Trinity River imply lower stability of the channel downstream of Dallas. Larger sediment is less cohesive, and calculations of stream power indicate the river is performing more work in the channel. If the sediment were of such a size to require higher entrainment velocity than what is observed in the river, its stability would be sound. This is not the case, however, making this increase in sediment size indicative of reduced channel stability. In the Brazos River, sediment size decreases downstream of urbanization, coinciding with reduced stream power. This indicates a river has maintained a stable state after the effects of urbanization.

3.4.2 Role of Sediment Size on Biogeomorphology

The influence of sediment size on biogeomorphology is direct and indirect. Fine sediment plays contrasting roles in this regard. Although a stabilizing abiotic force, it also readily adsorbs pollution, including trace metals, and poses a threat to sensitive lotic biota and their consumers (Salomons, 1985; Mohiuddin et al., 2009; Albertson and Allen, 2015). As contaminated suspended sediment settles to the bedload, it threatens benthic organisms and nekton which nest or overwinter in bed sediment. Many of the benthic organisms in the study area (Table 2) and the nesting/burrowing nekton (Table 1) are powerful destabilizers, and so from a purely geomorphological perspective this may stabilize threatened channels. From an ecological perspective, however, the results will be dire as populations which compose the diet of other lotic consumers diminish.

Other effects of sediment size are more direct. Major stabilizing organisms in these rivers were mayflies and caddisflies. Johnson et al. (2009) found that caddisfly larvae is significant influence on the stabilization of fine sediments, but in a study of two different sizes of small gravel, the impact of sediment size was negligible. Albertson and Daniels (2016) found that although caddisfly silk nets, in general, adapt well to increased amounts of fine sediment, certain species are less successful than others. For example, *Cheumatopsyche*, a genus prevalent in the Brazos River, did not adapt well to increased fine sediment (Moulton et al., 1993; Albertson and Daniels, 2016). The Brazos may also experience reduction in biofilm protection of bed sediment. As the stabilizing effects biofilms increase with particle size (Arnon et al., 2009), it is logical that this process will be reduced in the Brazos River downstream of Waco, where sediment size decreases.

In context of channel stability, sediment size is but one of several factors at work. Even with a focus on sediment size alone, one must consider the cohesiveness of fine sediment, the higher entrainment velocity required for coarse sediment, and the impact of fine sediment on biogeomorphological processes. Each river is unique in its response to these changes; rivers with lower discharges and smaller grain sizes are more heavily impacted by biotic factors, whereas those with higher discharges and larger grain sizes are dominated by physical forces, not biological (Moore, 2006; Albertson and Allen, 2015; Polvi and Sarneel, 2018). In this study, the rivers in the study area are low-gradient and generally low-velocity, making the biotic factors an important consideration in the overall stability of the river channel.

3.5 Conclusion

Sediment samples from the Brazos, Colorado, and Trinity Rivers in Texas were collected from sites upstream and downstream of major urban centers on the rivers and assessed for changes in sediment size. The Brazos River exhibited a gradual decrease in sediment size from sampling sites upstream of Waco to sites downstream of Waco, as average maximum sediment size decreased from 242 um to 193 um. The Trinity River exhibited a gradual increase in sediment size from sampling sites upstream of Dallas to sites downstream of

Dallas, as average maximum sediment size increased from 153-271 um, representing a change from fine sand to medium sand. Conventional channel stability studies indicate lower sediment sizes correspond to higher values of stability because of the cohesiveness of sediment and because this indicates lower rates of flow. A zoogeomorphological approach implies the same, as fine sediment may lead to reduction in populations of destabilizing fauna. Some stabilizing fauna such as silk-spinning caddisflies and mayflies and biofilm-producing bacteria, however, are also negatively impacted. Unique investigations to each river must be undertaken, then, to determine the overall effect of alteration of sediment size. These studies should incorporate stabilizing and destabilizing biota, including their respective population sizes. They could then be more adequately considered in an overall assessment of stability of the river. For the rivers in this study area, it is hypothesized that lower sediment sizes resulting from the effects of urbanization will contribute to morphologically stable river channels with potentially less ecological diversity. Higher average sediment sizes, then, are expected to contribute to ecologically diverse channels with increased lateral migration. Urbanization is here shown to impact each river in a unique manner.

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CHAPTER IV

LAND-USE AND LAND COVER AS DRIVERS OF MORPHOLOGICAL CHANGE IN RIVER SYSTEMS

4.1 Introduction

The fluvial environment is highly influenced by anthropogenic processes because of its favorability as a settlement site. From ancient civilizations' settlement on the Nile, the Tigris and the Euphrates, the Ganges, and the Brahmaputra to more recent metroplexes on the Trinity and Colorado Rivers in Texas, USA, River Thames in London and River Liffey in Dublin, rivers provide the lifeblood of many of the greatest cities on Earth. Over the last century, however, expansion of large urban centers and impervious area in the southern United States has altered the hydrologic cycle (O'Driscoll, 2010).

This paper reviews the direct and indirect roles of changes in land use and land cover (LULCC) on the fluvial system. I begin by giving an overview of the effects of LULCC and introduction of built structures on the fluvial system. Comparison of traditional LULCC and built structures associated with urbanization are compared with low-impact development methods. The effects of urban sprawl are also considered, because the fluvial systems in this study all experience gradational changes from rural to urban environments. Because modern fluvial systems are adapting to changes from both urbanization and climate change, I then discuss the effects of LULCC on climate change and the ensuing effects of climate change on the fluvial system.

Of the various methods by which humans alter their environment, change in land cover has the largest global impact (IPBES, 2019). Estimates of the amount of ice-free land affected by human action varies from 20% to 100% (Hooke, 2012; Wohl, 2013). These changes stem from human action involving moving earth or changing sediment fluxes, and many have indirect consequences that extend beyond the immediate spatial and temporal effects (Hooke, 2012). Even land left untouched is not immune to the effects of regional changes in land cover; patches of undeveloped land have been fragmented to 990,000 bodies of land roughly a square kilometer in area, causing habitat disconnect and fragmentation of natural geomorphic processes (Jacobsen et al., 2019). Hooke (1994, p. 845) remarked that, "One might ask how long such rates of increase can be sustained and whether it will be rational behavior or catastrophe that brings them to an end." Estimates that humans have modified over 50% of the land surface of Earth, reducing services which are provided, seemingly for free, from the plants, animals, insects, and microbes all sharing the ecosystem with humans (Hooke, 2012). In the last century, powerful technologies have enabled people to accelerate this process, prompting the suggestion that sustainability of the terrestrial environment is a more serious threat than climate change (Hooke, 2012). That being said, the terrestrial environment and climate change exist in a feedback relationship (Brown et al., 2014) which makes the respective effects difficult to distinguish; it is difficult to accurately determine what landscape alterations are the result of human activity, natural processes, or natural processes which have been modified by human activity (University of Maine, 2004).

This paper reviews current literature about the direct and indirect effects of LULCC associated with urbanization and suburbanization on the fluvial environment. I review prior studies on the direct effects of land cover change and engineering structures on hydrological processes related to river stability, as well as its indirect effects as a contributor to local and regional climate processes. Examples from three urbanized river systems in Texas are presented.

4.1.1 Effects of Landcover Alteration and Introduction of Built Structures

In this study, I consider the effects of the alteration of landcover and the introduction of specific built structures separately. Here, the alteration of landcover refers to replacement of one type of watershed surface with another. This may mean the replacement of native vegetation with agriculture or with an impervious surface typical of an urban environment, or the re-introduction of vegetation to a previously urbanized watershed. Built structures will refer to specific fluvial engineering structures intended to stabilize stream channels, often for the purpose of human safety in densely populated watersheds.

4.1.1.1 Effects of the Alteration of Landcover

The impact of anthropogenic influence on landscapes is not merely comparable to other geomorphic processes, but surpasses their effectiveness (Hooke, 1994; Szabó, 2010; Granados-Aguilar et al., 2020). The most apparent LULCC associated with urbanization is the increase in impervious landcover, which disrupts the natural water balance. In addition to an increase in impervious landcover, urbanization may increase demands for mining gravel for construction and expanded agricultural areas for food or energy needs. Conventional wisdom predicts that changes in land cover associated with urbanization or conversion to farmland leads to increased runoff, decreased evapotranspiration and decreased infiltration (Schlesinger et al., 1990; Zhang and Schilling, 2006; Suriya and Mudgal, 2012; Nugroho et al., 2013; Ahiablame et al., 2017). These effects directly alter processes in fluvial geomorphology and on slopes. Hydrological recovery can be induced by returning the watershed to its original cover, but scales of recovery vary. Zhu et al. (2014) assessed a watershed in which residential and commercial lands increased from 5.2% and 1.0% to 8.3% and 2.8%, respectively, and agricultural land decreased from 28.3% to 18.9% during the years 1984-2010. Despite efforts by the National Park Service which increased forested land from 65% to 69.5% during this time, SWAT simulation indicated a 3% increase in streamflow. Stream flows from forested sub-watersheds stabilized, but near urban centers streamflow increased by more than 10%. In a separate study from the Srepok watershed in Vietnam, forestation efforts increased forest cover by 41 hectares during the years 2000-2010, correlating with decreased surface, lateral, and groundwater flow (Quyen et al., 2014). Despite conventional wisdom regarding effects of LULCC on fluvial systems, interactions between site-specific factors (watershed slope, soil attributes, vegetation characteristics, climate, etc.) mean that standardized responsed by a watershed to alteration of land cover are unlikely (Guzha et al., 2018). Guzha et al. (2018), for example, found no significant trends in streamflow resulting from removal of forested lands in eastern Africa. In a 2013 study, alteration of grassland to farmland, forest, and urban areas in the Upper Du watershed in China did not exert a significant influence on either streamflow or sediment yield (Yan et al., 2013).

Mossa and McLean (1997) review the effects of mining gravel on a river in their study of the Amite River in Louisiana. The nature of channel adjustment is dependent on the nature of mining. Whereas in-channel mining causes adjustments in the channel bed, floodplain mining causes changes to channel position (Mossa and McLean, 1997). A decrease in armoring and thus stability may result from removal of coarse sediment for commercial usage (Lagasse et al., 1980), as can reductions in bed level (Bull, 1973). The presence of mining pits can have repercussions extending far from the pit itself (Mayer, 1972; Lee et al., 1993; Bull and Scott, 1974; Klondof, 1994). Mining also affects the water table (Morgan-Jones et al., 1984) and decreases channel sinuosity (Mossa, 1995).

LULCC takes many forms and it is useful to determine individual effects of various changes in land cover on the hydrological cycle when possible so that future planning may consider the effects of each. In the San Pedro Watershed, Miller et al. (2002) attributed increased streamflow to the simultaneous increase of urban, agriculture and woody mesquite land cover and decrease of grassland and desert scrub (Nie et al., 2011). Nie et al. (2011) recreated Miller's 2002 study and determined that urbanization was the strongest contributor to increased surface runoff, even though invasion of mesquite was the more prevalent change in land cover during the study period. Decreased baseflow in the watershed was attributed to the replacement of grassland and desert scrub by mesquite, but surface runoff is a stronger contributor to streamflow than baseflow in the study area (Nie et al., 2011). Thus, even relatively small levels of introduction of urban cover has a great impact on hydrologic processes compared to the effects of changes in vegetation. Similar results were obtained by Wijesekara et al. (2012) in their study area which saw a 65% increase in built-up areas, 20% in rangeland/parkland, and 1% in agriculture and decrease of 28% in deciduous, and 6% in evergreen forest. Modeling results indicated an increase of 7.3% in overland flow, and a decrease of 1%, 13.2%, and 2.3% in total evapotranspiration, baseflow, and infiltration, respectively, and a decrease of the total flow by 4%.

Clearly, one cannot generalize the effects of every LULCC decision for all watersheds. Planning and management of watershed development plays an important role in subsequent fluvial adjustments (Ozdemir and Elbasi, 2015) and expanse of urbanization alone is insufficient to predict hydrological response (Miller et al, 2014; Miller and Hess, 2017). Attempts to assess and predict fluvial adjustments must consider the pedology, vegetation, topography, and type of LULCC to each specific watershed and how it will be managed.

4.1.1.2 Introduction of Built Structures

Alteration of a watershed from the native land cover to an urbanized setting generally includes introduction of stabilizing structures on the river channels to minimize flooding and channel migration and allow for efficient transmittal of storm water from a city. These efforts to mitigate hydrological hazards to city residents require modification of the fluvial system. Conventional stormwater conveyance systems, for example, are designed to collect, convey and discharge runoff as efficiently as possible (USEPA). This creates a highly efficient drainage system, but also decreases groundwater recharge, increases the volume of runoff and changes the timing, frequency and rate of discharge. These changes can cause flooding, water quality degradation, and enhanced stream erosion (USEPA). Dams and levees are positive-relief structures which alter river morphology upstream and downstream of the structure. Upstream of a dam, sediment accumulates and lowers channel slope (Owens, personal observation), introducing a new local base level which increases lateral channel erosion upstream of the dam and augments floodplain landforms. Downstream of the dam, landform development varies based upon management. The decrease in sediment flux and regular flow downstream of a dam often leads to narrower channels and, as flooding is typically reduced by dams, floodplain features are less pronounced (Owens, personal observation).

The type of dam and management should be considered in any assessment of a modified river channel. Dam management which does not release water from its impoundment in anticipation of coming precipitation will increase flooding upstream of the dam and cause flashier flows downstream, leading to less stable channels with higher rates of migration. Rivers with numerous dams in sequence have further altered geomorphology, as the downstream effects of one dam are not dissipated before the upstream effects of the next dam occur. The morphology of a reach affected by multiple dams is distinct from the typical upstream or downstream effects of singular dams (Jefferson et al., 2013).

Levees are positive relief structures which trend parallel to river channels as flood control measures. Though effective as flood-control measures, the augmented banks cause adjustment of the overall drainage pattern, sometimes leading to formation or pronunciation of yazoo tributaries. The presence of levees also leads to more pronounced backswamps, as water from unusually high floods is less apt to drain back into the channel once the flood has passed. Reduction of flooding in the immediate vicinity of rivers means that excess energy is less frequently expended overbank to the adjacent floodplain but is directed downstream. Higher rates of flow are, thus, experienced in the channel more frequently, causing downstream regions to experience increased erosion, which leads to channel migration and cutoff loops.

4.1.1.3 Low Impact Development

Traditional urban and suburban development put watersheds at risk by creating large tracts of impervious area, eliminating natural infiltration and buffer zones (Davis, 2005). The impacts of urbanization on hydrology and water quality can be minimized with the use of low impact development (LID) practices in urban areas (Ahiablame, 2013). LID is a site design strategy with a goal of maintaining or replicating the predevelopment hydrologic regime using design techniques to create a functionally equivalent hydrologic landscape (Dietz, 2007). Pioneered in the early 1990s in Prince George's County, Maryland, several LID projects have since been implemented (Davis, 2005). The process begins during site preparation. Rather than clear-cutting or leveling large expanses of land, designers leave as much natural vegetation as possible on each lot and avoid disturbing natural topographic depressions (Davis, 2005). Roads are kept as narrow as zoning will allow, sidewalks and driveways are reduced, and the use of heavy machinery is avoided to avoid soil compaction. LID techniques such as rooftop retention, permeable pavements, bioretention and disconnecting rooftop rain gutter spouts can easily be used in urban areas to address pollutant removal and the protection of predevelopment hydrological conditions (Cheng et al., 2001; Lloyd, 2001; Coffman and France, 2002; France, 2002; Davis, 2005; Scholz & Grabowiecki, 2007; Fassman & Blackbourn, 2010), especially by reducing runoff and promoting infiltration (Hood et al., 2006; Collins et al., 2008; Bedan and Clausen, 2009). Importantly, these techniques also promote ecosystem connectivity, and may reduce impacts of landscape fragmentation.

Basic LID principles include conservation of natural features, minimization of impervious surfaces, hydraulic disconnects, disbursement of runoff and phytoremediation and can be implemented using such as bioretention facilities or rain gardens, grass swales and channels, vegetated rooftops, rain barrels, cisterns, vegetated filter strips and permeable pavements. These are summarized in Table 12.

Table 12: Low-impact development methods

LID Method	Result
Grass buffer strips	Reduce runoff velocity; filter particulate matter
Sand beds	Provide aeration, drainage; flushes pollutants from soil
Ponding areas	Provide storage for runoff; allows for settling of particles and evaporation of excess water
Introduction of organic layers	Provides medium for growth of microorganisms to degrade petroleum-based pollutants.
Introduction of planting soils	Promotes plant growth, contain clays which adsorb pollutants.
Introduction of vegetation	Pollutant removal; uptake of excess water
Vegetated Roof Covers	Extension of the life of roofs, energy cost reduction, and conservation of land that would otherwise be required for stormwater runoff controls.
Permeable pavements	Preservation of infiltration capacity, lake and wetland quality.
Downspout disconnection (Rerouting of rooftop runoff to rain barrels, cisterns, or permeable areas)	Reduction of runoff, preservation of infiltration, reduction of water usage from domestic supplies.
Planter box	Collect and absorb runoff, filtering pollutants
Urban tree canopies	Reduction and slowing of stormwater, reduction of urban heat island effects
Land conservation	Reduction of the effects of stormwater runoff, protection of biodiversity, carbon sequestration

Ahiablame (2013) showed that LID practices could be effective in managing urban stormwater at the watershed scale using rain barrel/cisterns and porous pavements. In two watersheds, various levels of rain barrel/cistern and porous pavement implementation resulted in 2–12% reduction for runoff, total phosphorous, and total nitrogen for the two watersheds. Baseflow and baseflow pollutant loads increased in the two watersheds, more or less, by 1%, whereas 1–9% reduction occurred in total streamflow and associated pollutant loads with the reduction of runoff in the watersheds. Ahiablame recommends implementation of 50% rain barrel/cistern, 50% porous pavement, and 25% rain barrel/cistern combined with 25% porous pavement as good options stakeholders should consider for retrofitting in urbanized watersheds (Ahiablame, 2013). Gunn et al. (2012) suggest that planners and developers be encouraged to incorporate swales and mature trees to minimize hydrologic impacts of land development; swales transmit stormwater runoff with lower velocity than low-permeability or impervious surfaces, allowing more infiltration, sedimentation, and filtration. Mature trees promote evapotranspiration, interception, and infiltration (Gunn et al., 2012). Land developments with small lots, wide roads, and little tree cover had the highest effects on hydrology, but development with conservation design reduced the impacts on hydrology and produced a hydrologic response similar to that of a forested scenario (Gunn et al., 2012).

Effects of urbanization on the hydrological cycle can also be mitigated by modifying the introduced structures, such as the inclusion of green roofs. Green roofs may be extensive or intensive, with extensive green roofs being thin (≤10cm) with drought-tolerant vegetation. Intensive green roofs, conversely, may have thick vegetation including trees and shrubs (Gregoire & Clausen, 2011). Gregoire & Clausen (2011) find that extensive green roofs intercept, retain, and evapotranspire between 34% and 69% of precipitation with an average retention of 56%.

More quantitative information is needed which describes potential impacts of LID practices at the watershed scale (Ahiablame, 2013). Previous research has focused its attention on runoff management, but because of the potential impacts of LID practices on baseflow, impacts on baseflow at the watershed scale need to be investigated. Additionally, little information is available for exploring LID practices as retrofitting technologies at the watershed scale (Ahiablame, 2013).

4.1.1.4 Low-Density Urban Sprawl

This study focuses on three rivers which flow through urbanized watersheds. None, however, make a sudden transition from rural to urban channels. Rather, all experience the gradational urbanization levels typical of cities in United States. Low-density urbanization, or urban sprawl, has increased in the United States in recent years (Pendall, 1999). The growth of urban sprawl is not a perfect representation of population increase. From 1982 and 1992, for example, urban land increased by 25%, whereas population increased by only 11% (Pendall, 1999). Such a rapid increase is likely associated with the declining costs of personal transportation, rising costs of urban living, and job opportunities outside the city center (Irwin and Bockstael, 2007). This is problematic from an environmental standpoint because it consumes green space, promotes dependency on personal vehicles, pressures environmentally sensitive areas, and contributes to landscape fragmentation (USEPA; Irwin and Bockstael, 2007). Its intensity, however, is not necessarily linearly related to distance from the high-density urban center. Irwin and Bockstael (2007) investigated the growth of urban sprawl in Maryland and found that areas that experienced the largest gains in fragmentation were located relatively far from urban areas and experienced concurrent increases in the proportion of low-density residential land.

The impact of urban sprawl and low-density urbanization (or suburbanization, as it is also known) on landscape geomorphology is immense as a result of the demands it places on natural resources. Alberti et al. (2007) examined how urban patterns influence ecological conditions. Change in landscape associated with urbanization, particularly sprawl, has been significant during the last half century and is expected to continue through the next decades. Across US metropolitan areas, land consumption has been outpacing population, with most urban areas expanding at about twice the rate of the population growth. (Alberti et al., 2007). Su et al. (2010) computed a ratio of the growth of urban land to the loss of natural ecological land and assessed the way that urban sprawl affects change of natural patterns in the landscape and connectivity using the Western Taihu Lake watershed in China. For this study, we postulate that human activities are the greatest stressors at the scale of the watersheds supporting individual tributary streams (Alberti et al., 2007).

4.1.2 Landscape Connectivity

Landscape connectivity, or the degree to which the landscape facilitates or impedes movement among resource patches, is an important component of landscape health and stability. Connectivity is disrupted by changes to the spatial relationships between natural and modified land parcels, which fragments land and disrupts habitat, hydrological functions, albedo effects, and resources (Su et al. 2010).

A more efficient means of providing space for people should be enacted if we are to conserve the integrity of the natural system. Rather than lateral expansion of cities which consumes and fragments native land, perhaps vertical expansion should be considered. Future research may address the role of densely spaced tall buildings, as opposed to sparsely-spaced short and wide ones, on albedo and effects of urban heat islands. From the perspective of landscape ecology and geomorphology, this approach to city development is favorable for its condensation of anthropogenic alterations and availability of higher amounts of land to be left in or restored to a natural state (Alberti et al., 2007).

4.1.3 Land Use and Land Cover as a Contributor to Climate Change

LULCC can contribute to climate warming by increasing the albedo of the land surface and producing urban heat islands. This complicates assessment of the respective influences of LULCC and climate change, as one contributes to the other. Further, the combined results of the two will affect hydrological components differently depending on the temporal scale of interest (Pervez et al., 2015). LULCC in the form of vegetation removal and/or urbanization increases albedo of the land surface and removes vegetation which naturally recycles carbon dioxide. The global radiative forcing by changes in surface albedo may be comparable with that because of anthropogenic aerosols, solar variation and several of the greenhouse gases (Pielke et al., 2002). In more populated regions, the local radiative-forcing change caused by surface albedo may be greater than that resulting from various well-mixed anthropogenic greenhouse gases together (IPCC, 2001). Kalnay and Cai (2003), for example, observed a decrease in the diurnal range of temperatures resulting from land-use changes and estimate 0.27^{o}C mean surface warming per century resulting from these changes. Puspita (2019) observed that the change in land use occurring during the years 2003-2016 increased carbon emissions in Bandung, Indonesia and projected a temperature increase in the city by an average of 1^{o}C in 2031. This increase is attributed to the surface heat emitted by the land and has occurred despite allocation of protected areas and parks to reduce the overall temperatures of the land surface.

Effects resulting from climate change will work on a different time scale than effects of direct alteration to watershed cover, and so differentiating between the effects of each will help city planners and land managers make prudent decisions regarding sustainable land alteration. LULCC change alters regional and global climate through the surface-energy budget, the effects of which may be more important to climate than the effects of the carbon cycle, but more difficult to quantify (Pielke et al., 2002).

4.1.3.1 Effects of Urban Heat Islands

Urbanization commonly leads to an urban heat-island effect which increases air temperature directly above and around the city and may lead to alteration in localized weather patterns. Since 1818 (Howard, 1818), the urban heat island (UHI) has been recognized as an urban or metropolitan area experiencing warming temperatures than its rural surroundings because of large amount of heat generated from urban structures which consume and re-radiate solar radiations, and from anthropogenic heat sources (Rizwan, 2008). This is considered as one of the major problems in the 21st century posed to human beings as a result of urbanization and industrialization of human civilization (Rizwan, 2008).

UHIs provoke changes to nearly every element of the hydrological cycle. O'Driscoll et al. (2010) shows that the UHI can induce urban rainfall, as urban surfaces are generally drier and release more heat than surrounding rural areas. The urban heat island can alter convection of air masses in urban areas and modify air circulation by the surface roughness and urban canopy (buildings, infrastructure, or trees). Bornstein and Lin (2000) showed that the urban heat island effect caused convective activity in Atlanta that was responsible for the occurrence of three out of six summer storms studied. Similarly, Burian and Shepherd (2005) analyzed data from 19 rain gauges in the Houston area before and after urbanization and found that during the warm season the urban area had 59% more rainfall than an upwind control area. The urban area also had 80% more occurrences of warm season rainfalls and the mean warm season precipitation amount increased by

25% in the urban area from a pre- to post-urban time period. Rates of evapotranspiration (ET) are changed directly by alteration of the land surface and indirectly by impacts of the UHI. ET can be the dominant water flux in catchment water budgets in the southern U.S., but few published studies have directly evaluated the effects of urbanization on ET in the southern U.S. (O'Driscoll et al., 2010). According to Dow and DeWalle (2000), a watershed that reaches 100% urban land use would exhibit a reduction of ET of approximately 22 cm/yr.

Land management is essential to reducing the effects of the UHI, not simply land planning. Puspita (2019) recommends that merely allocating green space in cities is insufficient to reduce UHI effects. Such efforts must be complemented by detailed directions on each type of land use change that can later be followed up in zoning regulations in a detailed spatial plan.

4.1.3.2 Effects of Climate on the Fluvial System

Having discussed the how LULCC contributes to a changing and increasingly variable climate, I will now complete the loop by examining the effects of that same changing and variable climate on the fluvial system. Adjustments to river channels do not occur solely as a result of changing land use-land cover (LULCC). Coupled with the rapid expansion of urban centers (Lund, 2017; Ura and Daniel, 2018; United Nations, 2015), the terrestrial environment is subject to the effects of climate variability and climate change. To predict future geomorphic activity of a river, therefore, the effects of rapid urban population growth must be considered with the concurrent climate variability and the processes of climate change. Deciphering what changes to a fluvial system result directly from LULCC and what result from climate change is a distinct challenge in the Anthropocene (Miller and Hutchins, 2017).

4.1.3.3 Effects of the Variability of Global Climate Change on Stability of a Stream

Other studies examine stream power as an indicator of fluvial geomorphic stability and assess the role of urbanization in the stream power of rivers in the study area. Stream power determines the ability of a river to transport sediment and perform geomorphic work and is an important factor for predicting adjustment of a river channel. Climate change and variability will affect stream power differently with varying location, but each factor must be considered so that prediction of channel adjustment can be localized and, thus, relevant for the region in question. Discharge and water density are the factors likely to be most variable by region, because runoff and groundwater contribution (contributing to discharge) is spatially variable, as is the rate of evaporation (contributing to salinity). Should these two variables remain stable, stream power will decrease as a result of climate change/variability, because channel slopes will likely decrease. Channel slopes will likely decrease over long time scales because of climate change/variability. Studies have predicted an increase in sediment supply resulting from climate variability (Istanbulluoglu and Bras, 2006), which can lead to aggradation of bed sediment and decrease in channel slope. Climate change/variability will also lead to adjustments in sea level (Goy et al., 2003; McCarthy et al., 2015).

River discharge will be affected by changes in precipitation, runoff, and groundwater contribution to gaining streams. Precipitation will likely increase in most regions as high-precipitation events such as ENSO/La Nina are amplified by climate change (Redmond and Koch, 1991; Slade and Chow, 2011) yet runoff is predicted to decrease in some locations (Bouwer et al., 2006; Ma et al., 2008; Ma et al., 2010; Wang et al., 2012) and increase in others (Chen et al., 2007; Jiang et al., 2011; Chen et al., 2012). Groundwater level is predicted to decrease as a result of climate variability (Vaccaro, 1992; Chen et al., 2004). Accordingly, predictions of variations in discharge will need to be assessed locally, based on predictions of precipitation and runoff, and subsurface hydraulics.

Water density will be affected by water temperature and water salinity. Water temperature is determined by air temperature, vegetative cover, and volume. Climate models which predict a decrease in vegetative cover indirectly predict an increase in water temperature resulting from reduction of shade. Water temperature is positively correlated with air temperature and negatively correlated with volume (Chang and Lawler, 2011; Van Vliet et al., 2013). Salinity is a factor of sediment contribution, predicted to increase because of climate variability (Istanbulluoglu and Bras, 2006) and rate of evaporation, predicted to vary by hemisphere (Miralles et al., 2014). Efforts to predict changes in water density by climate variability will need to consider local variability in water temperature, which will increase or decrease density as water temperature fluctuates around 40°F (4.4°C), and salinity, which is positively correlated with water density.

4.1.3.4 *Effects of Climate vs. LULC*

The interconnectedness of LULC with climate change makes distinguishing the respective effects of each supremely difficult. It seems that for every study stating that increased stream flow and flooding is more strongly correlated to LULCC than climate change (Du et al., 2012; Neupane and Kumar, 2015; Ozdemir and Elbasi, 2015; Lei and Zhu, 2018), others insist that climate change is more strongly correlated to hydrological alterations than LULCC (El-Khoury et al., 2015; Fan and Shibata, 2015; Serpa et al., 2015;

Even with general agreement that LULC does alter the hydrologic cycle, it is difficult to predict the level of change which will result from the alteration of land cover. Franczyk and Chang (2009) predicted that an 8–15% expansion of urban land use in the Rock Creek basin (Portland, Oregon), would only result in a 2.3–2.5% increase in annual depths of runoff. This may be because when impervious area increases, the direct runoff increases while the baseflow decreases, so that the total runoff does not increase considerably (Du et al., 2012). Not all hydrologic events respond to changes in landcover in the same manner. In the Du et al. (2012) study, urbanization changed the amount of annual runoff in dry years more greatly than in wet years, making water availability in dry years more sensitive to urbanization. In some studies, smaller floods are more affected by urbanization than larger ones and peak flows and runoff volumes were more strongly affected than long-term runoff (Hollis, 1975; Booth, 1988; Changnon et al., 1996; Bhaduri et al., 2001; Beighley et al., 2003; Konrad, 2003; Choi and Deal, 2008; Du et al., 2012). Although Du et al. (2012) found that flood discharge and volume were more affected by urbanization than annual runoff or flood peak, respectively, urbanization had little effect on annual runoff. In other studies, however, (Brun and Band, 2000 and Wissmar et al., 2004), urbanization had a strong role in long-term hydrologic processes.

4.2 Effects of LULC on the Brazos, Colorado, and Trinity Rivers in Texas, United States

4.2.1 Study Area

To assess the role of LULC on stream channel characteristics, three major rivers in Texas are considered, each of which flow through an urban center. Changes in stream power, sediment size, and overall channel morphological stability is assessed upstream and downstream of urbanization, allowing for a general evaluation of the role in urbanization on hydraulic characteristics. In this study, changes to these channel features are compared to the characteristics of land cover of the HUC-12 watershed of each reach, as indicated by the 2016 National Land Cover Database (NLCD).

The Brazos River extends 1,352 km from the confluence of its Salt Fork and Double Mountain Fork in Stonewall County to its mouth in the Gulf of Mexico near Freeport in Brazoria County (Hendrickson, 2019) (Figure 29).

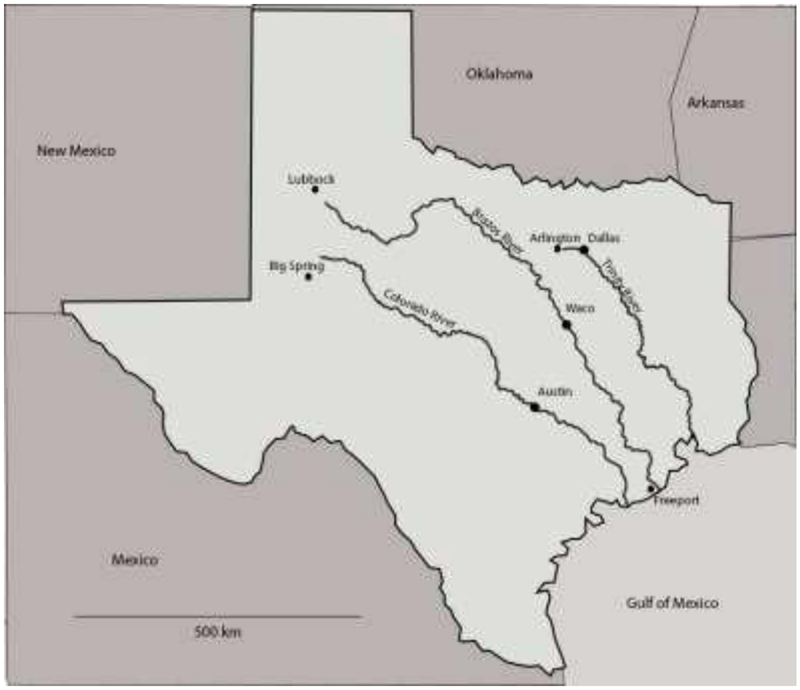


Figure 29: Location of rivers assessed in this study.

This study examines a ~27 km reach beginning ~12 km upstream of the city of Waco and extending ~11 km downstream of Waco. Upstream of Waco, the Brazos River flows through land covered predominantly with pastureland and cultivated crops. The banks become modified by medium-impact development within the city of Waco. Immediately downstream of Waco, land cover returns to pastureland and more cultivated agricultural land than in the upstream reaches (Figure 30).

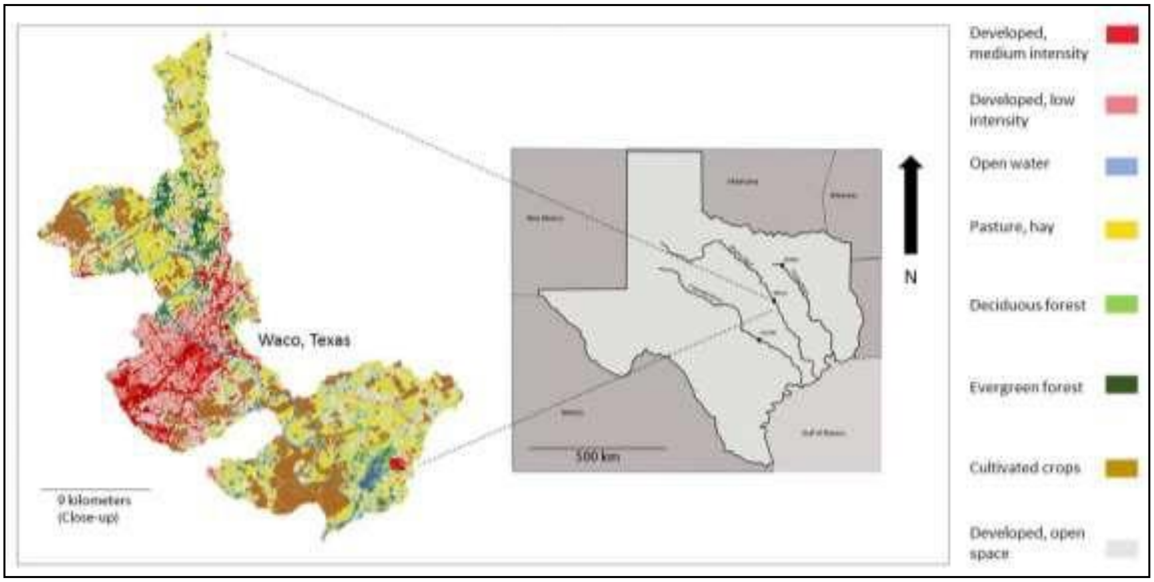


Figure 30: Types of land cover in the Brazos River watersheds assessed in this study.

The Colorado River extends 1,387 km from its headwaters to the Gulf of Mexico and has a total drainage area of 103,341 km^2 (Kammerer, 1987). This study assesses the river in the vicinity of Austin, Texas. Urban sprawl associated with Austin extends significantly to the northwest, following the Colorado River upstream. For this reason, observations of the river in a natural state upstream of Austin urbanization and suburbanization had to occur near Smithwick, Texas, approximately 50 miles (80.5 km) northwest of Austin (Figure 31).

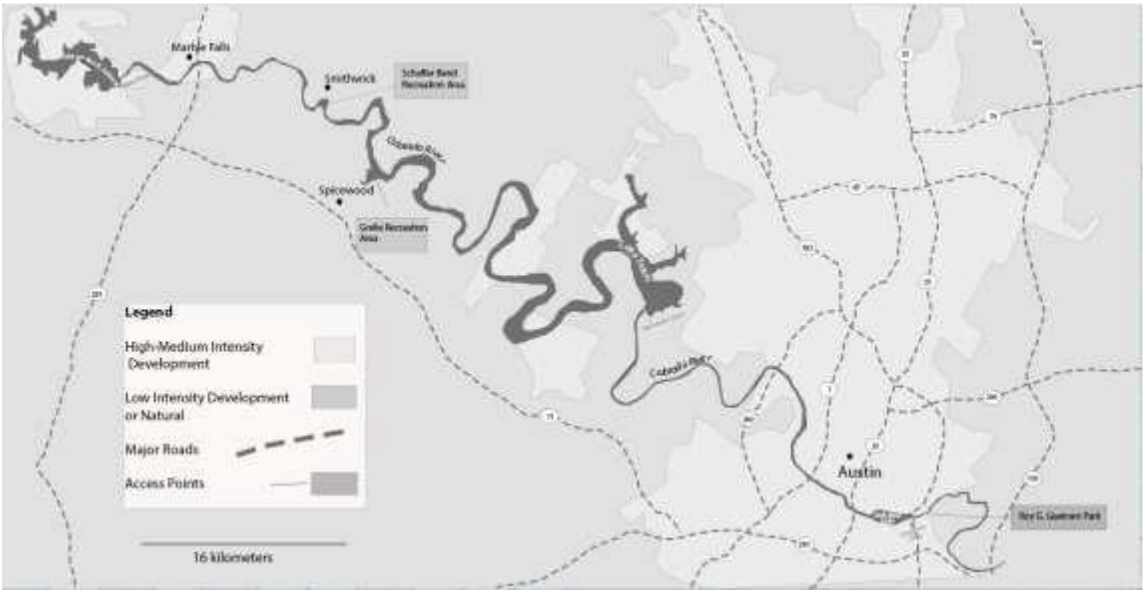


Figure 31: Study reaches on the Colorado River near Austin, Texas

The Colorado River was accessed downstream of Austin at the Roy G. Guerrero Park near Longhorn Dam. Downstream of Austin, the Colorado River flows through a natural channel with undeveloped banks (Figure 32).

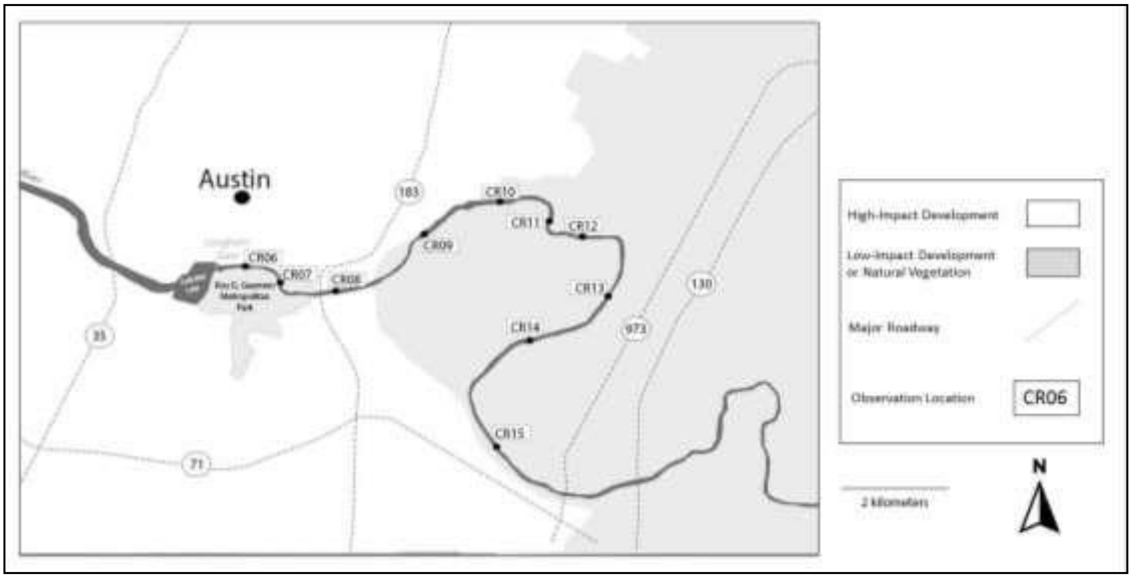


Figure 32: Studied reach of the Colorado River downstream of Austin, Texas

In the upstream reaches, land cover is mostly undeveloped or developed with low impact. Forest, grassland, and scrub/shrub are the predominant land cover types (Figure 33).

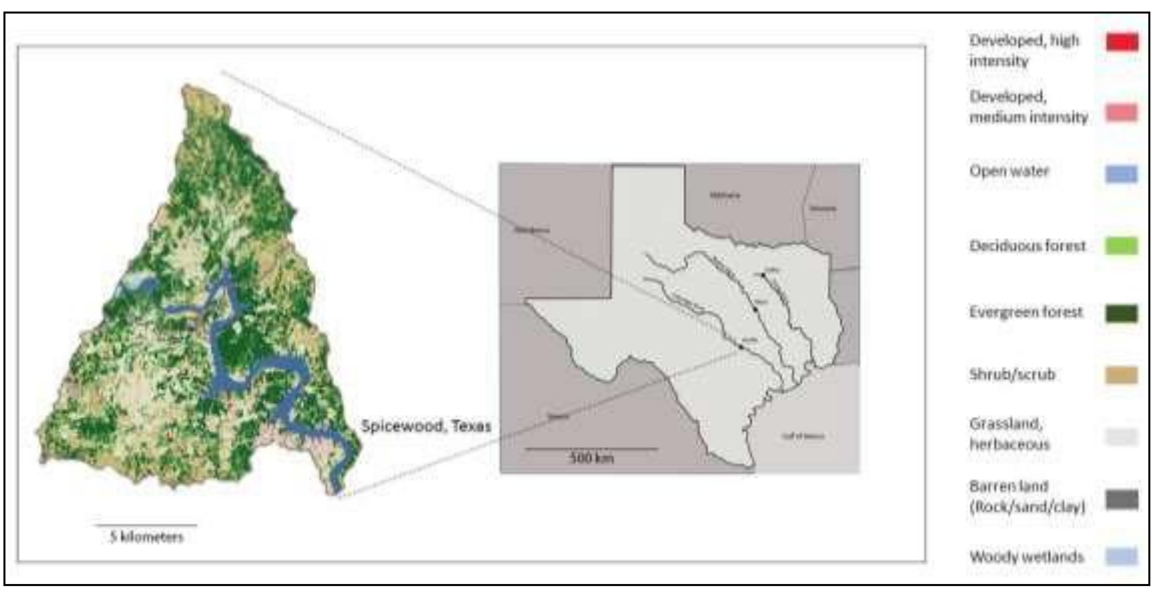


Figure 33: Land cover in the upstream reaches of the Colorado River.

In Austin, development with high and medium intensity dominates. Immediately downstream of the city, land cover changes to pasture/hay (Figure 34).

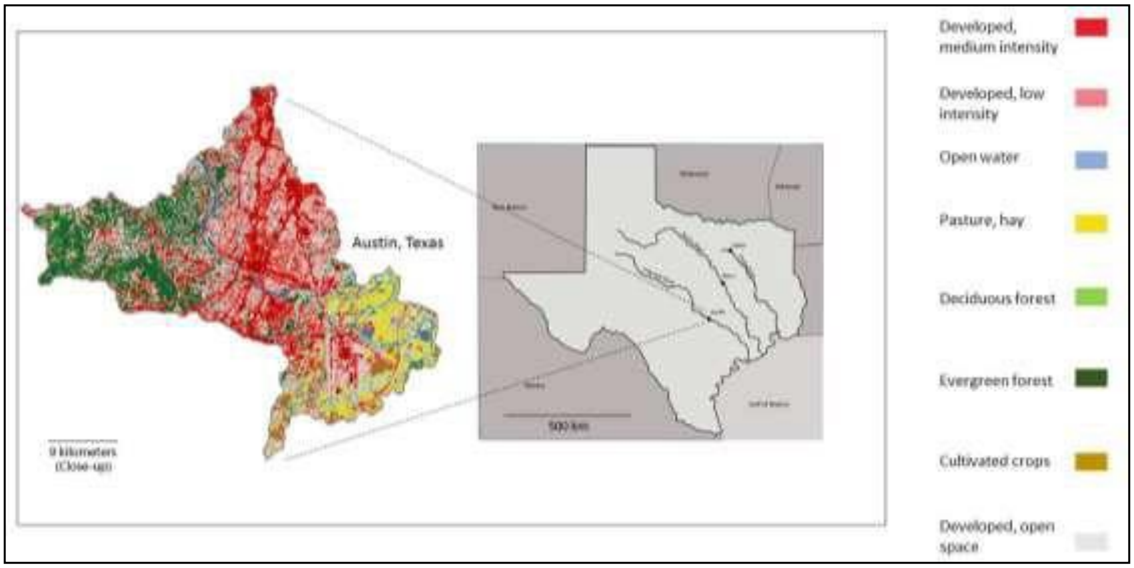


Figure 34: Types of land cover in Colorado River watersheds assessed in this study, in and downstream of Austin.

The Trinity River originates at the confluence of West and Elm Forks northwest of Dallas, Texas and east of Arlington, Texas. It extends 1,142 km to its mouth at Trinity Bay in Chambers County, Texas (Figure 35).

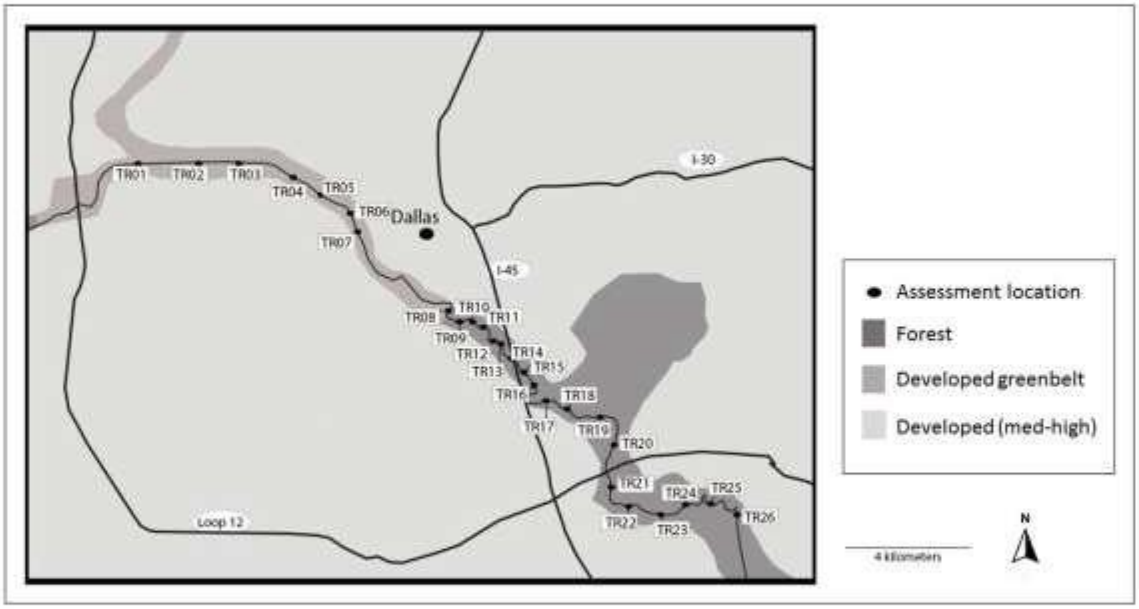


Figure 35: Observed reaches of the Trinity River near Dallas, Texas.

Assessment begins at the confluence of the West Fork and Elm Fork, marking the origin of the Trinity River main channel. Although this reach is geographically within an urbanized region of the Dallas-Fort Worth-Arlington metroplex, the channel is unaltered by engineering structures and retains a wide greenbelt on either bank extending nearly half a kilometer on each side of the river. As the river turns southwest through the city of Dallas, the greenbelt ceases to exist, and the channel is reinforced with concrete. Downstream of the city center, the river channel is flanked by the Great Trinity Forest, a natural evergreen forest (Figure 36).

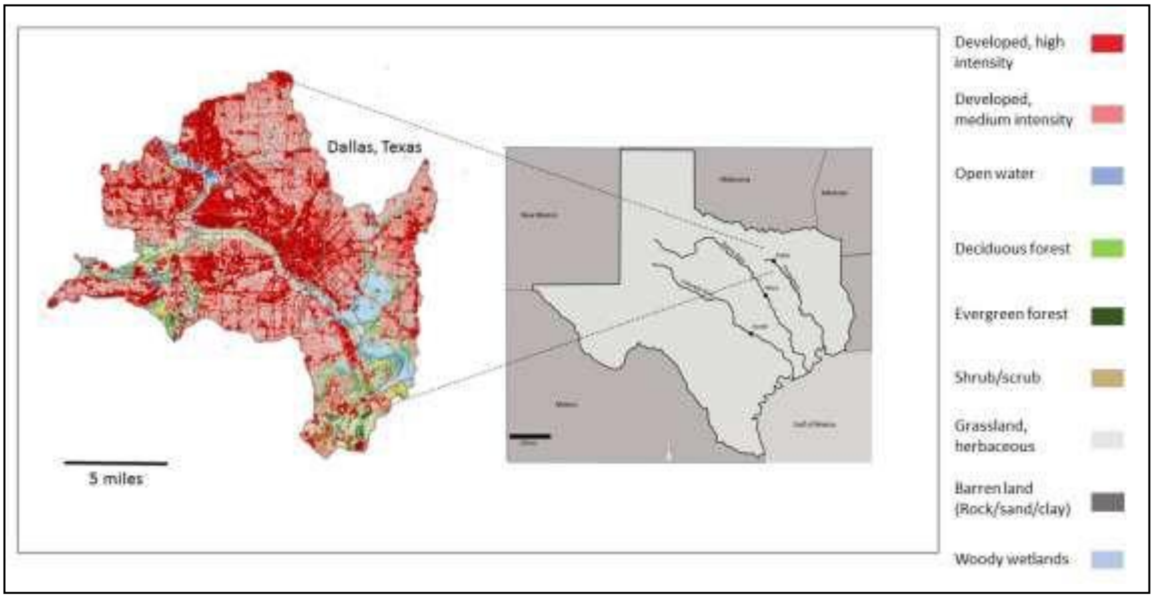


Figure 36: Types of land cover in Trinity River watersheds assessed in this study.

4.2.2 LULC on the Brazos, Colorado, and Trinity Rivers

Imagery of land cover was obtained from the 2016 NLCD and clipped to the HUC-12 watersheds for study reaches of each river. Stability assessment of the Trinity River began in the Turtle Creek- Trinity River Watershed 120301050102, whereas sediment sampling and stream power calculations began further upstream in Delaware Creek – West Fork Trinity River 120301020706. All assessment progressed downstream through Turtle Creek – Trinity River 120301050102 and Five Mile Creek – Trinity River 120301050108. The headwaters of the Trinity River begin at the confluence of West Creek and Elm Creek in HUC 120301050102. Here, developed open space and low intensity development dominate as the maintained Dallas Floodway and Trinity River Greenbelt Park span the length of the reach (Figure 37). This sub-watershed is flanked by more heavily developed sub-watersheds lacking greenbelts. The river in this reach progresses from a natural channel to a heavily channelized one, all within a wide greenbelt.

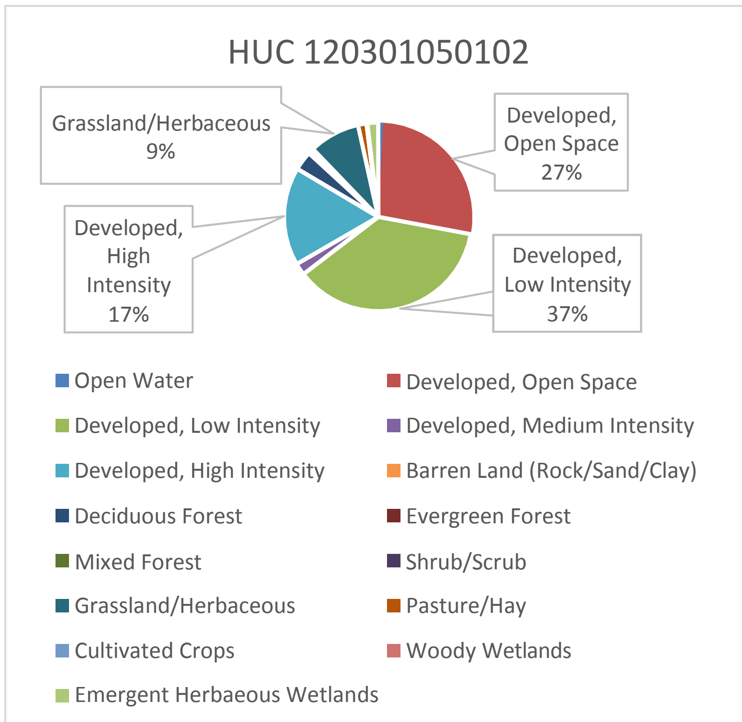


Figure 37: Land cover in HUC 120301050102, headwaters of the Trinity River near Dallas, Texas.

Farther upstream, the West Fork in HUC 120301020706 flows through a more heavily developed sub-watershed (Figure 38). Natural riparian vegetation is preserved in Mountain Creek Preserve in the southern portion of the sub-watershed, but most of the land is developed by sprawl of Irving and Dallas.

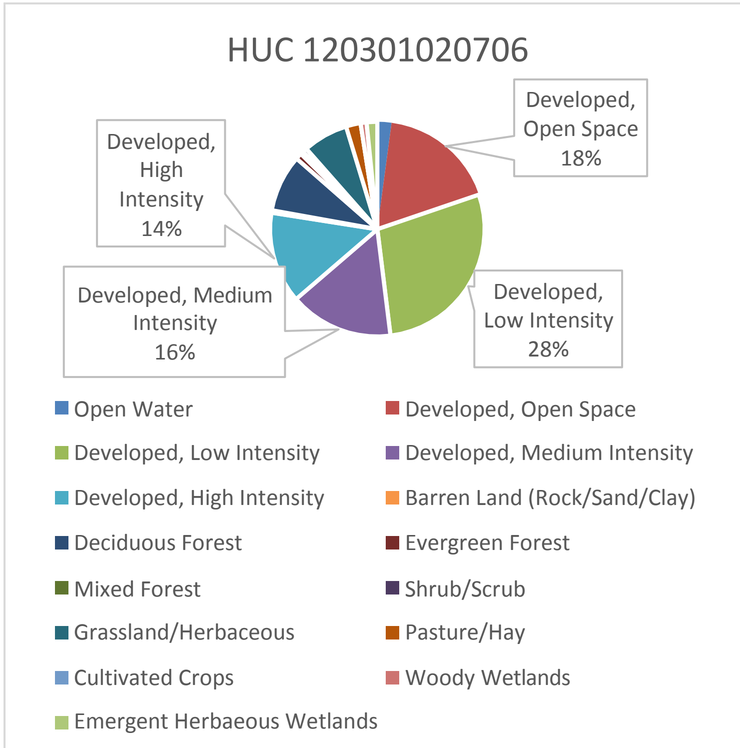


Figure 38: Land Cover in HUC 120301020706, immediately upstream of the headwaters of the Trinity River.

Sub-watershed 120301050108 consists of the southeastern extent of Dallas sprawl, which transitions quickly to the Great Trinity Forest. Accordingly, land cover in this region is approximately half developed and half natural vegetative cover such as woody wetlands, grasslands, evergreen forest, pasture, and emergent herbaceous wetlands (Figure 39). Generalized representations of developed and undeveloped land in each watershed is presented in Figure 40. A detailed list of the types of land cover is presented in Table 13.

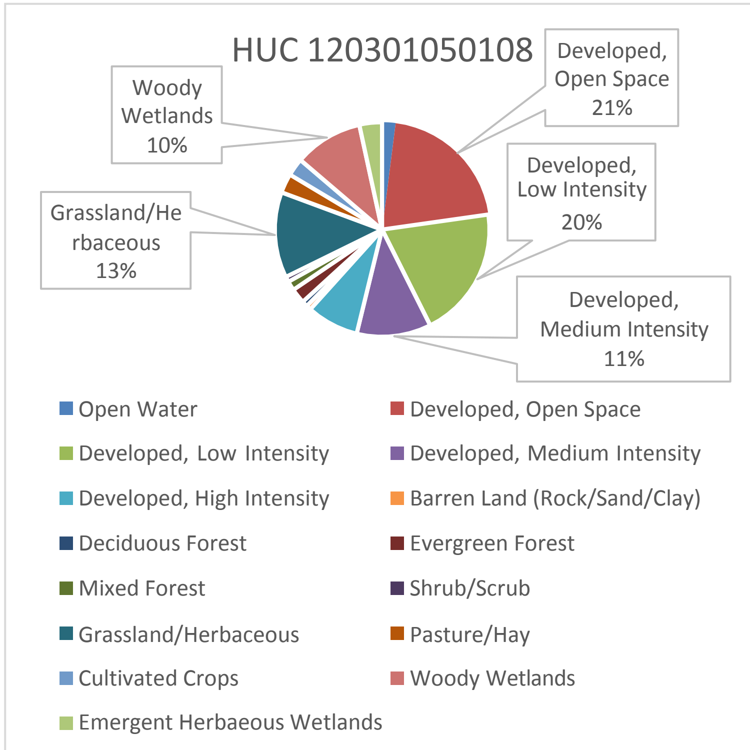


Figure 39: Land cover in HUC 120301050108, immediately downstream of Dallas, Texas.

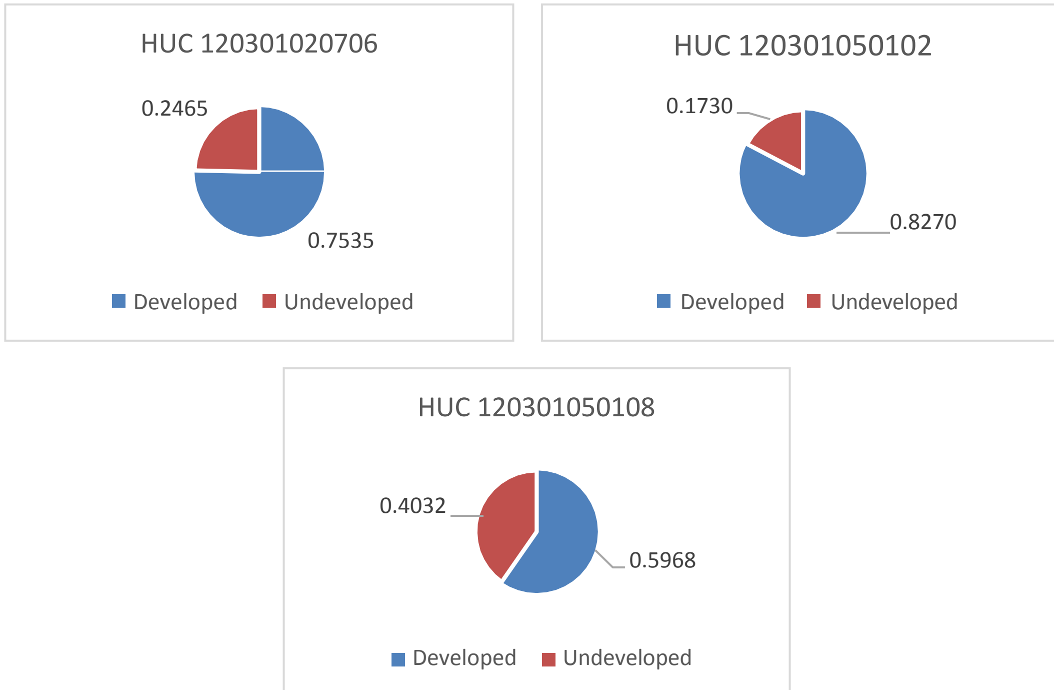


Figure 40: Percentages of developed and undeveloped land in each studied watershed of the Trinity River.

Land Type	120301020706	120301050102	120301050108
Open Water	0.021193	0.008469	0.01996958
Developed, Open Space	0.176675	0.270873	0.207636197
Developed, Low Intensity	0.282525	0.366721	0.198403742
Developed, Medium Intensity	0.156645	0.020591	0.112204177
Developed, High Intensity	0.137675	0.168767	0.07860262
Barren Land (Rock/Sand/Clay)	0.003407	5.82E-05	0.006967273
Deciduous Forest	0.086222	0.032771	0.008635494
Evergreen Forest	0.009583	0.00221	0.022684526
Mixed Forest	0.004374	0.002792	0.014032677
Shrub/Scrub	0.006567	0.004874	0.008283859
Grassland/Herbaceous	0.068138	0.087437	0.129025399
Pasture/Hay	0.022078	0.014577	0.02928381
Cultivated Crops	1.03E-05	2.33E-05	0.026683349
Woody Wetlands	0.008883	0.001222	0.103429665
Emergent Herbaceous Wetlands	0.016026	0.018614	0.03415763

Table 13: Proportions of various land cover types in the studied watersheds of the Trinity River.

Assessment of the Brazos River began in the White Rock Creek- Brazos River Watershed 120602020801 and progressed downstream through Cottonwood Creek – Brazos River 120602020803 and Manos Creek – Brazos River 120602020805. In the most upstream watershed, 120602020801, land cover is dominated by pastures and hay (32%), grasslands (22%), and cultivated crops (15%) (Figure 41). In HUC 120602020803, development increases to 64% as the Brazos flows through the city of Waco and Baylor University (Figure 42). Downstream of Waco, land cover quickly returns to predominantly grassland/herbaceous (22%), pasture/hay (30%), and cultivated crops (26%) (Figure 43). Figure 44 presents proportion of developed land versus undeveloped. Table 3 presents a detailed listing of land types.

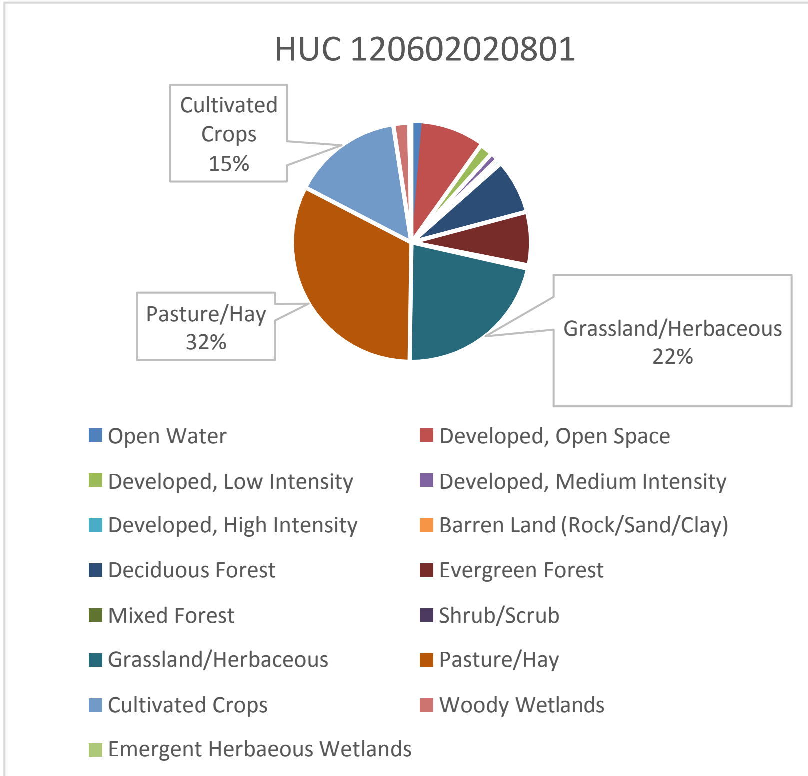


Figure 41: Land cover of HUC 120602020801, immediately upstream of Waco, Texas.

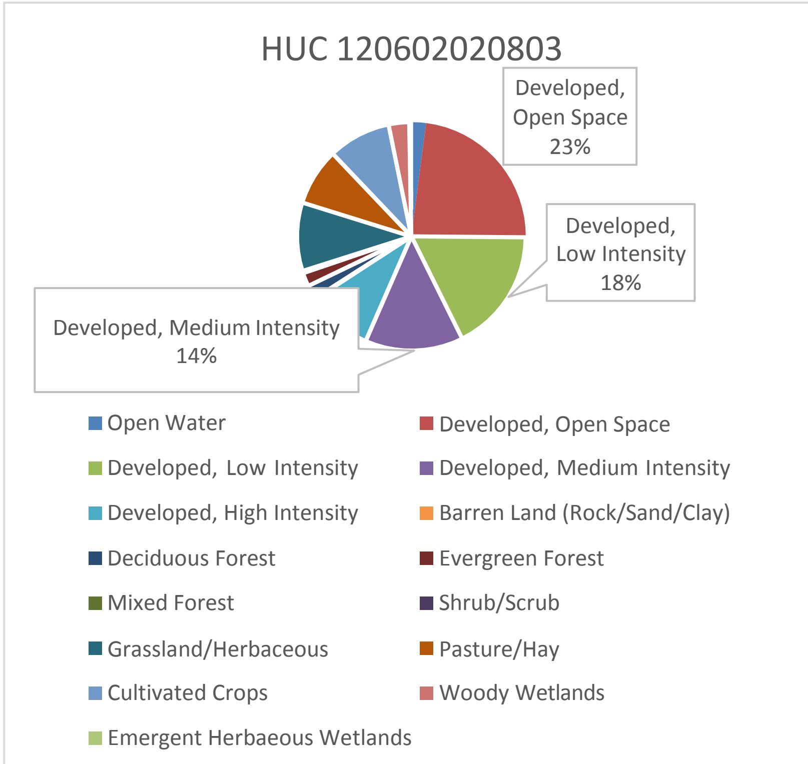


Figure 42: Land cover in HUC 120602020803, which contains downtown Waco.

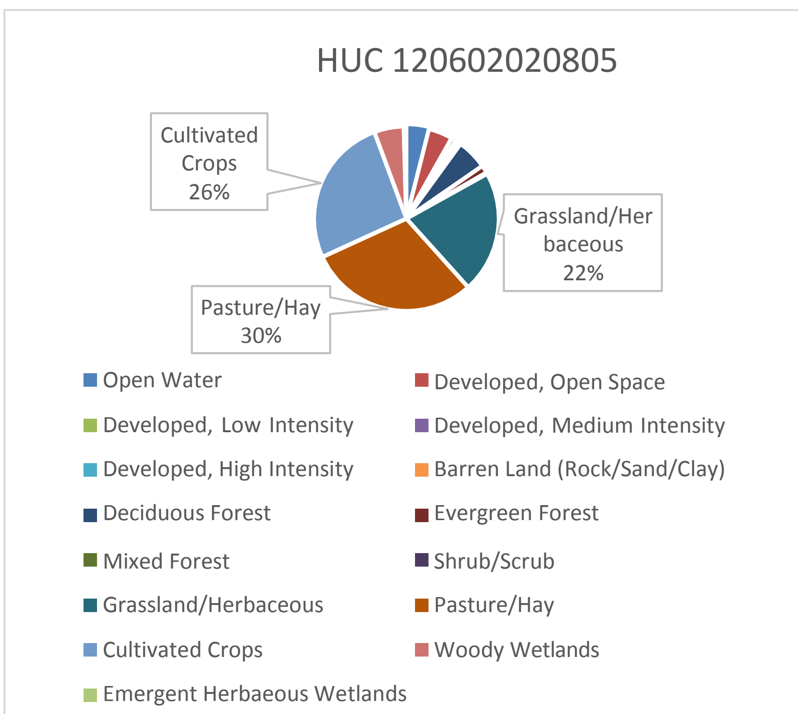


Figure 43: Land cover in HUC 120602020805, downstream of Waco.

Figure 44: Developed and undeveloped land in the study watersheds.

Land Type	120602020801	120602020803	120602020805
Open Water	0.0135	0.0207	0.0391
Developed, Open Space	0.0853	0.2305	0.0424
Developed, Low Intensity	0.0180	0.1754	0.0084
Developed, Medium Intensity	0.0111	0.1388	0.0057
Developed, High Intensity	0.0060	0.0925	0.0033
Barren Land (Rock/Sand/Clay)	0.0010	0.0011	0.0008
Deciduous Forest	0.0738	0.0195	0.0536
Evergreen Forest	0.0726	0.0193	0.0136
Mixed Forest	0.0031	0.0015	0.0015
Shrub/Scrub	0.0011	0.0015	0.0008
Grassland/Herbaceous	0.2171	0.0971	0.2142
Pasture/Hay	0.3237	0.0810	0.2981
Cultivated Crops	0.1494	0.0890	0.2621
Woody Wetlands	0.0215	0.0289	0.0518
Emergent Herbaceous Wetlands	0.0029	0.0030	0.0044

Table 14: Proportions of various types of land cover in the studied watersheds of the Brazos River.

Assessment of the Colorado River begins in HUC 120902050201, Hickory Lake – Lake Travis and HUC 120902050202, Little Cypress Lake – Lake Travis. Both watersheds are in the region of Spicewood, Texas and Smithwick, Texas, upstream of urban sprawl associated with Austin. Downstream assessment begins in HUC 120902050306, Town Lake – Colorado River and progresses through HUC 120902050409, Carson Creek – Colorado River. In the watersheds upstream of Austin, land cover is dominated by natural vegetation in the form of grassland/herbaceous, shrub/scrub, deciduous forest, and evergreen forest (Figure 45). In the Town Lake watershed, the southern portion of downtown Austin creates a 98% developed watershed (Figure 46) which then progresses to the Carson Creek watershed and mixed cover of vegetation (66%) and development (34%) (Figure 47). An overview of developed vs. undeveloped area is presented in Figure 48 and detailed listing in Table 7.

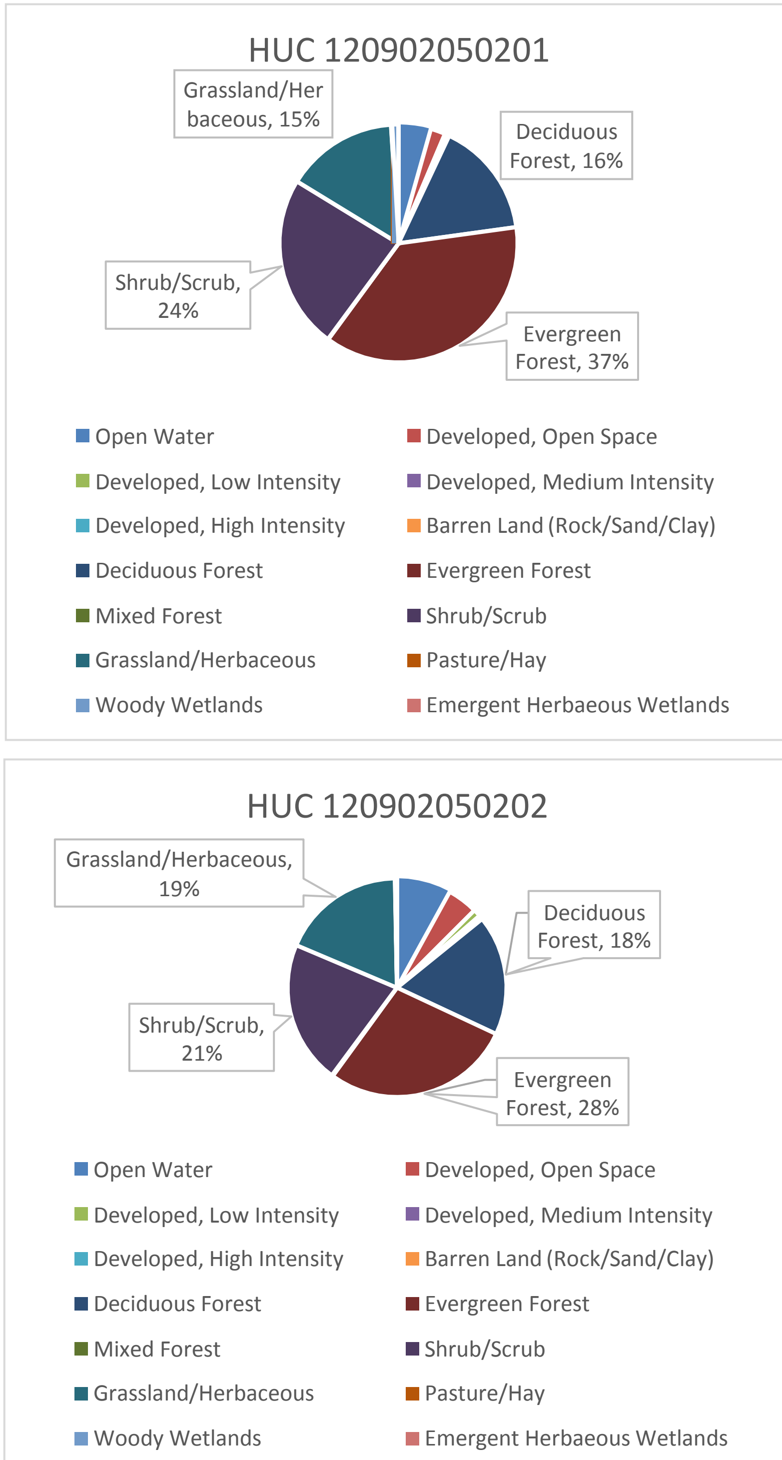


Figure 45: Land cover in the two studied watersheds upstream of Austin, Texas.

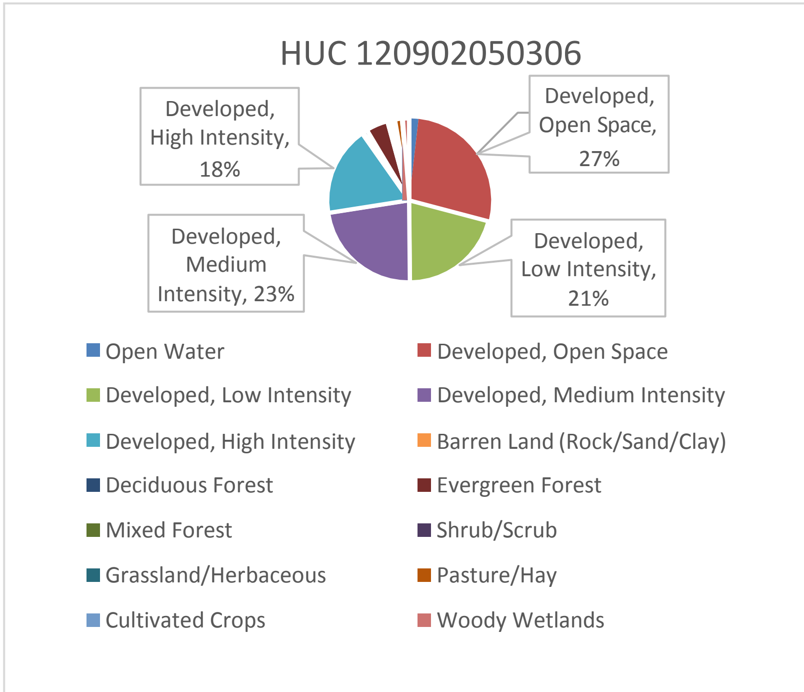


Figure 46: Land cover in HUC 120902050306, consisting of parts of Austin and area just downstream.

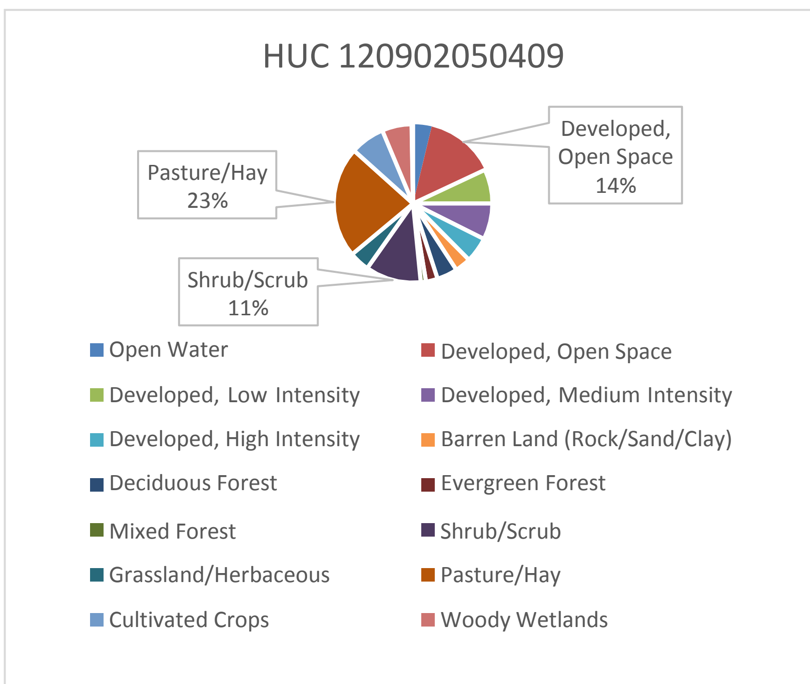


Figure 47: Land cover in HUC 120902050409, downstream of Austin

Figure 48: Developed vs. undeveloped land in the studied watersheds near Austin, Texas.

Land Type	120902050201	120902050202	120902050306	120902050409
Open Water	0.0439	0.0799	0.0183	0.0378
Developed, Open Space	0.0199	0.0451	0.2728	0.1423
Developed, Low Intensity	0.0049	0.0108	0.2074	0.0699
Developed, Medium Intensity	0.0004	0.0024	0.2269	0.0742
Developed, High Intensity	0.0000	0.0003	0.1771	0.0516
Barren Land (Rock/Sand/Clay)	0.0010	0.0032	0.0031	0.0324
Deciduous Forest	0.1580	0.1780	0.0084	0.0417
Evergreen Forest	0.3725	0.2804	0.0433	0.0239
Mixed Forest	0.0007	0.0016	0.0011	0.0106
Shrub/Scrub	0.2359	0.2120	0.0081	0.1134
Grassland/Herbaceous	0.1525	0.1833	0.0060	0.0417
Pasture/Hay	0.0015	0.0003	0.0135	0.2269
Cultivated Crops	0.0000	0.0000	0.0017	0.0704
Woody Wetlands	0.0086	0.0024	0.0121	0.0605
Emergent Herbaceous Wetlands	0.0001	0.0003	0.0003	0.0027

Table 15: Proportions of various types of land cover in the studied watersheds of the Colorado River.

4.2.3 Role of LULC on Overall Channel Stability on Three Coastal Plains Rivers

Overall channel stability is assessed using morphological indicators in a method developed by Doyle et al. (2000); a modification of the method by Johnson et al. (1999). Johnson et al. (1999) present a weighted average of 13 indicators of stability, each ranked excellent, good, fair, or poor (Table X). Each indicator of stability was given a pre-assigned weight based on its influence on channel morphology and ranked excellent (1-3), good (4-6), fair (7-9), or poor (10-12). This procedure was developed to determine stability of gravel-bed rivers at road crossings and culverts to avert bridge failure resulting from channel adjustment and was implemented on streams in Pennsylvania and Maryland, then modified by Doyle et al. (2000) for application to gravel streams in Indiana. It is used in this study, with modification, to assess morphological stability of three low-gradient Coastal Plain rivers: the Brazos, the Colorado, and the Trinity. In this assessment, higher numerical values indicate greater instability of the channel.

A comparison of the ratings of channel instability and amount of development in the watershed is presented in Figure 49. A more detailed comparison of the ratings of channel instability and level of development is presented in Figure 50.

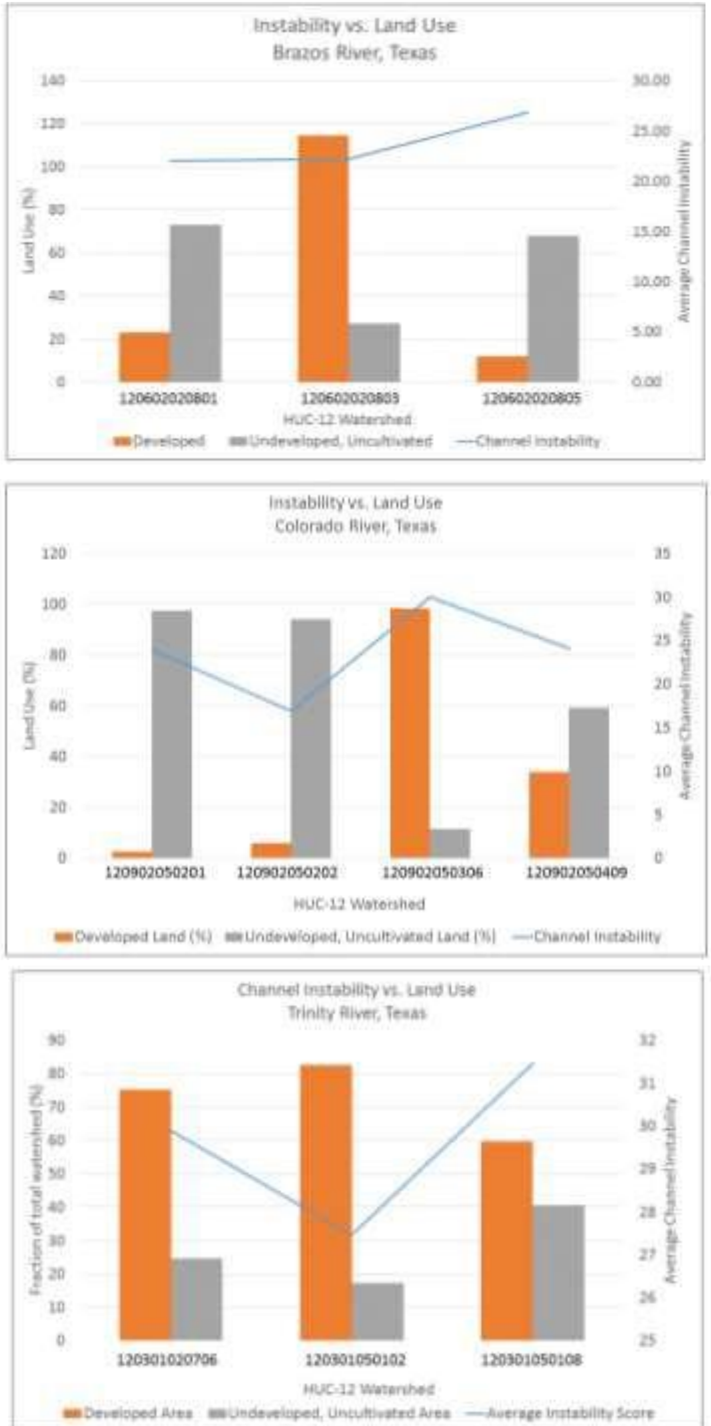


Figure 49: Comparison of channel stability and amount of land development in the studied watersheds.

Figure 50: Comparison of channel instability with level of development in three studied watersheds.

4.2.4 Comparison of Land Cover with Sediment Size

In assessment of morphological stability of river channels, sediment size is an important consideration for its influence on abiotic and biotic factors. Migration of a river channel is a function of stream power and sediment size (Nanson and Hickin, 1986), therefore, any influence which adjusts stream power or sediment size will alter the stability of the channel. In sand- and gravel-bed rivers, Nanson and Hickin (1986) found that basal sediment size was particularly influential in determining the rate of erosion. Hickin and Nanson (1984) found basal sediment size to be the most important variable reflecting bank erosion-resistance for sizes ranging from clay to large boulders. Doyle et al. (2000) considers sediment size in assessment of channel stability, with fine sediment sizes correlating to high scores of stability and sand or loamy sand correlating to low scores of stability. Fine sediment is generally more cohesive than coarse sediment, and so it follows that fine-grained channels will be more stable in natural rivers. Dams may make this standard less reliable by changing a high-flow river to low-flow. In this circumstance, coarse bed and/or bank sediment may remain in the channel although flow has been altered such that velocity of entrainment is rarely, if ever, achieved. The presence of coarse sediment, then will imply a lower rating of stability according to Doyle et al. (2000) even though the channel will rarely experience velocities of flow sufficient to transport the sediment.

Bed sediment was sampled from multiple locations in each watershed and sieved to size ranges of 425 µm – 2mm, 250-425 µm, 125-250 µm, 75-125 µm, and <75 µm. The

D50 and average sediment size was calculated, and compared to land cover. Results for the Brazos River are presented in Figure 51. Decrease in sediment size corresponded to reduction in grassland, pasture, and cultivated crops immediately upstream (Figure 52).

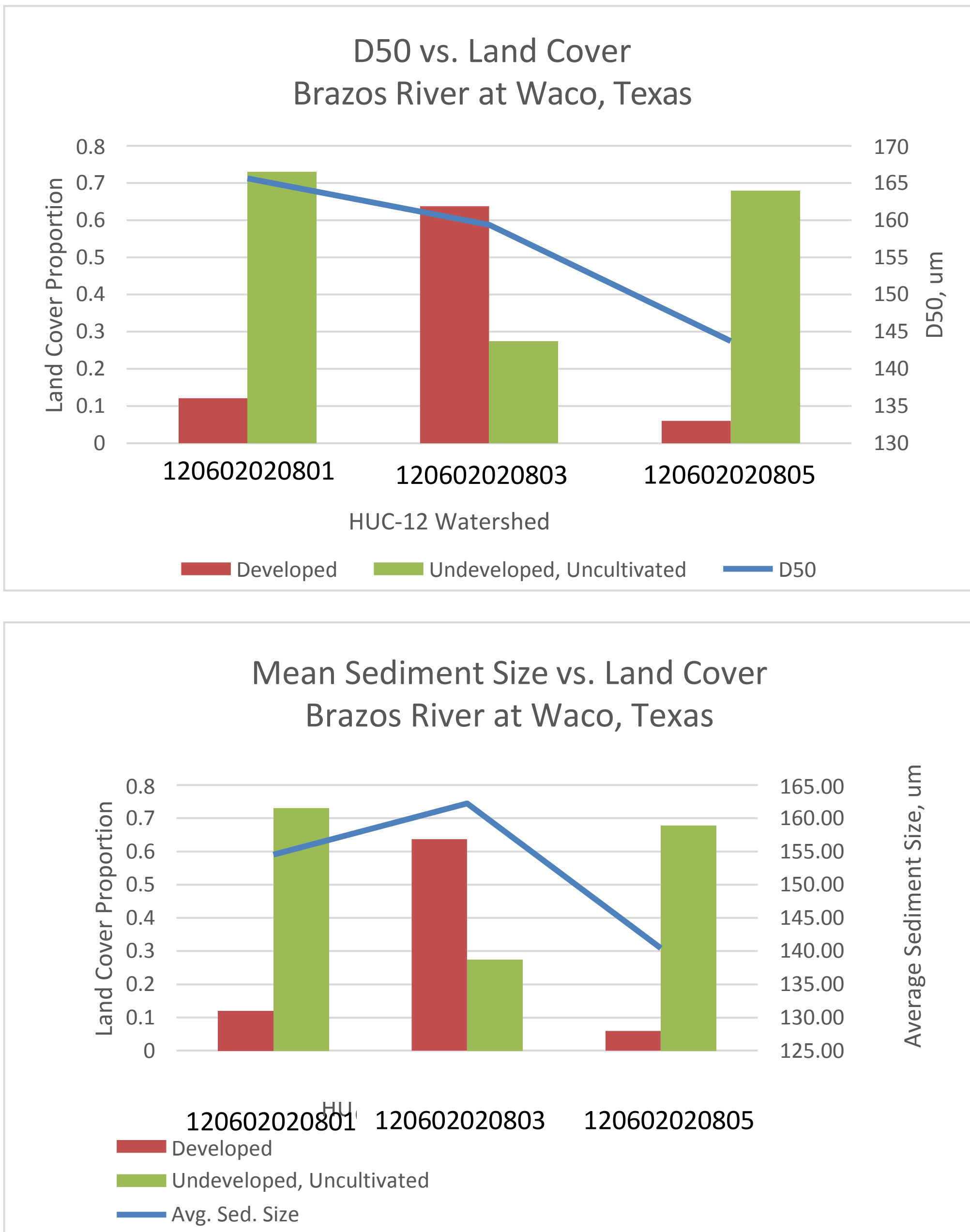
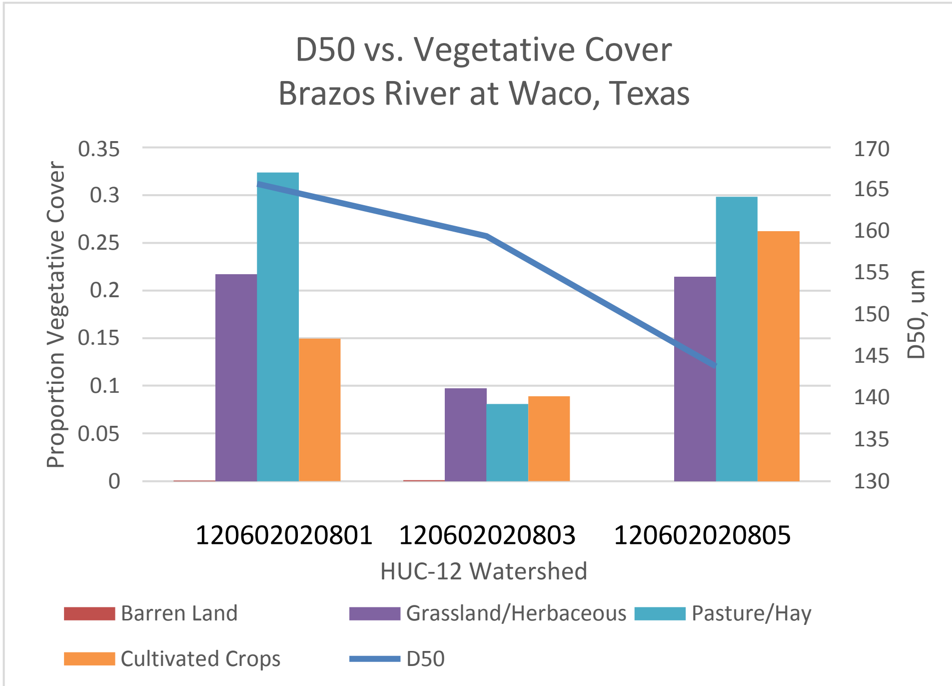


Figure 51: Comparison of D50 and mean sediment size and land cover in the Brazos River at Waco.



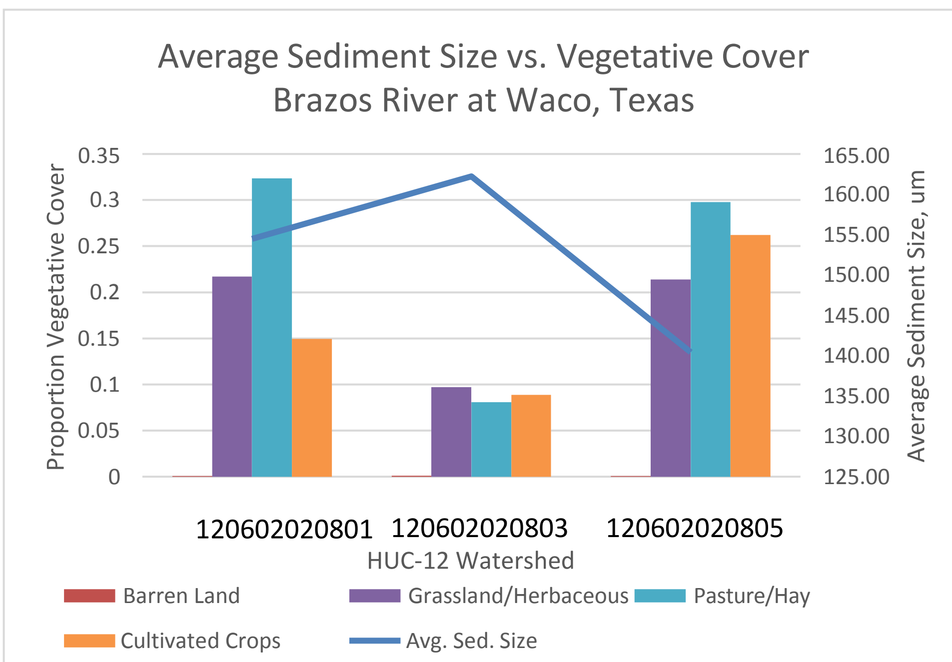


Figure 52: Comparison of median and mean sediment size with vegetative cover in studied watersheds of Brazos River.

Mean and median sediment size in the Brazos River remained in the very fine sand category, though sizes decreased by 13% and 10%, respectively, downstream of the more highly developed watershed Figures 53 and 54 show the relationship of sediment size to forest and type of wetland.

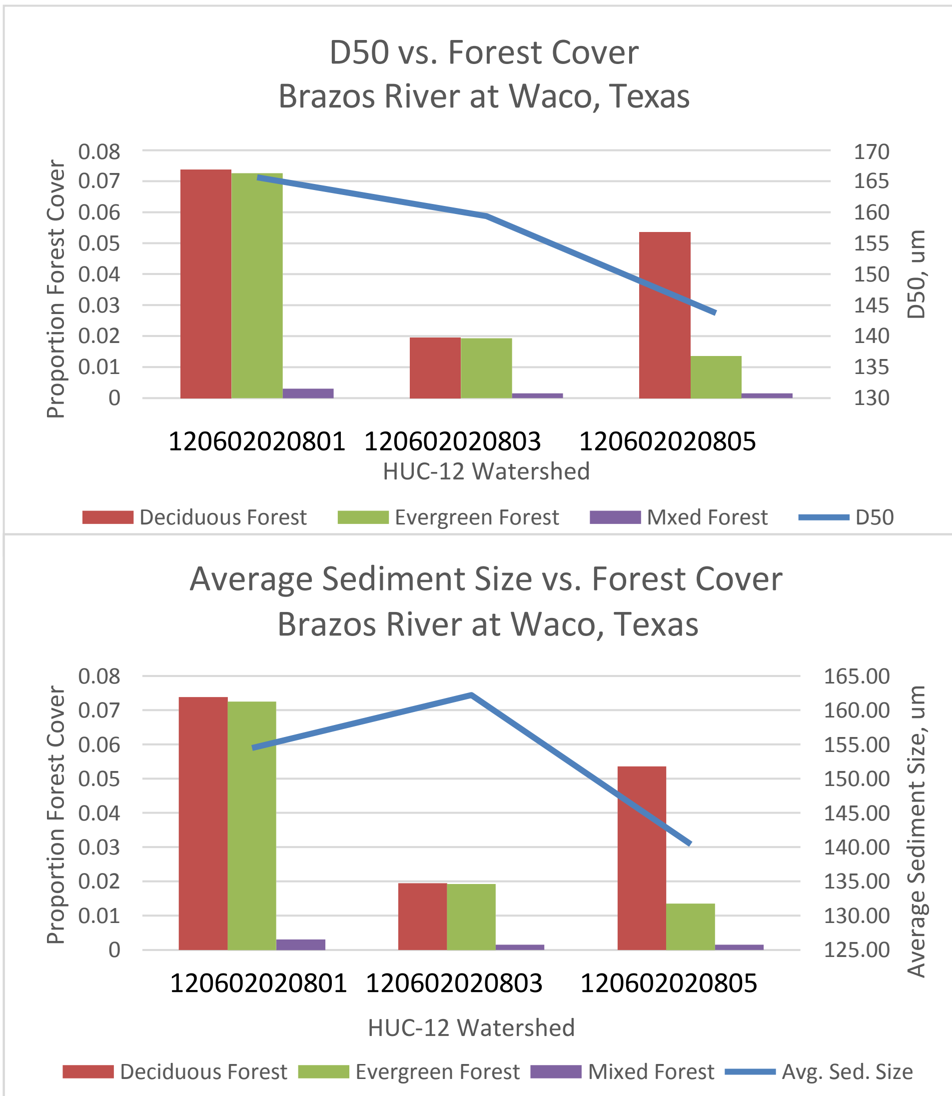
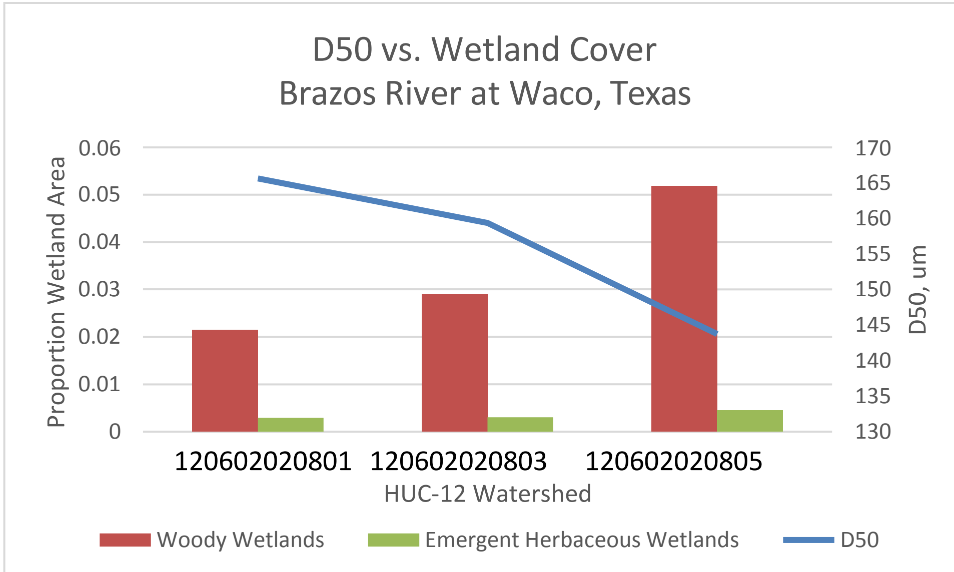


Figure 53: Comparison of median and mean sediment size to forest cover in the Brazos River near Waco.



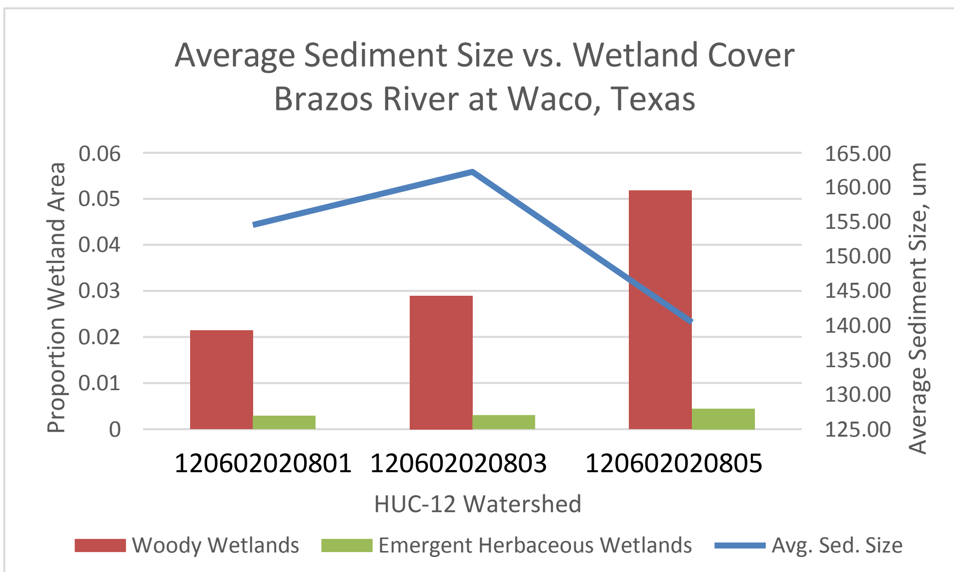
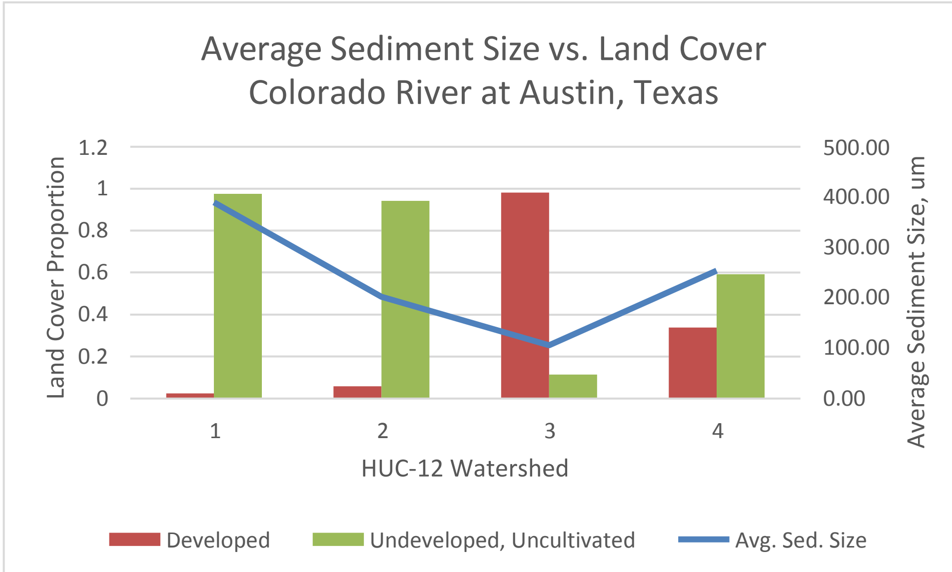


Figure 54: Comparison of median and mean sediment size to wetland cover in the Brazos River at Waco.

A comparison of sediment size to level of development is presented in Figure 55.



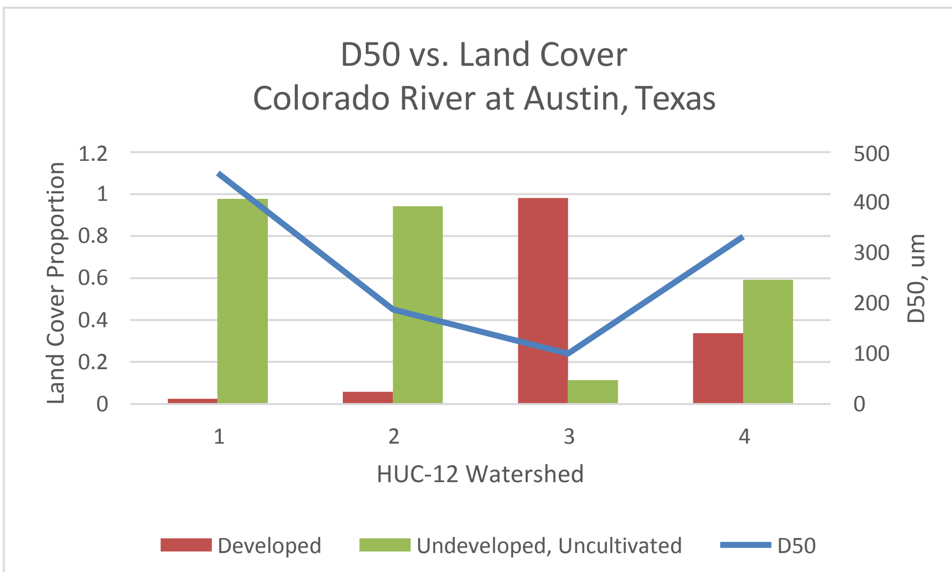


Figure 55: Comparison of land cover type and sediment size in the Colorado River near Austin, Texas.

A comparison of sediment size to land cover on the Colorado River is presented in Figures 56-58.

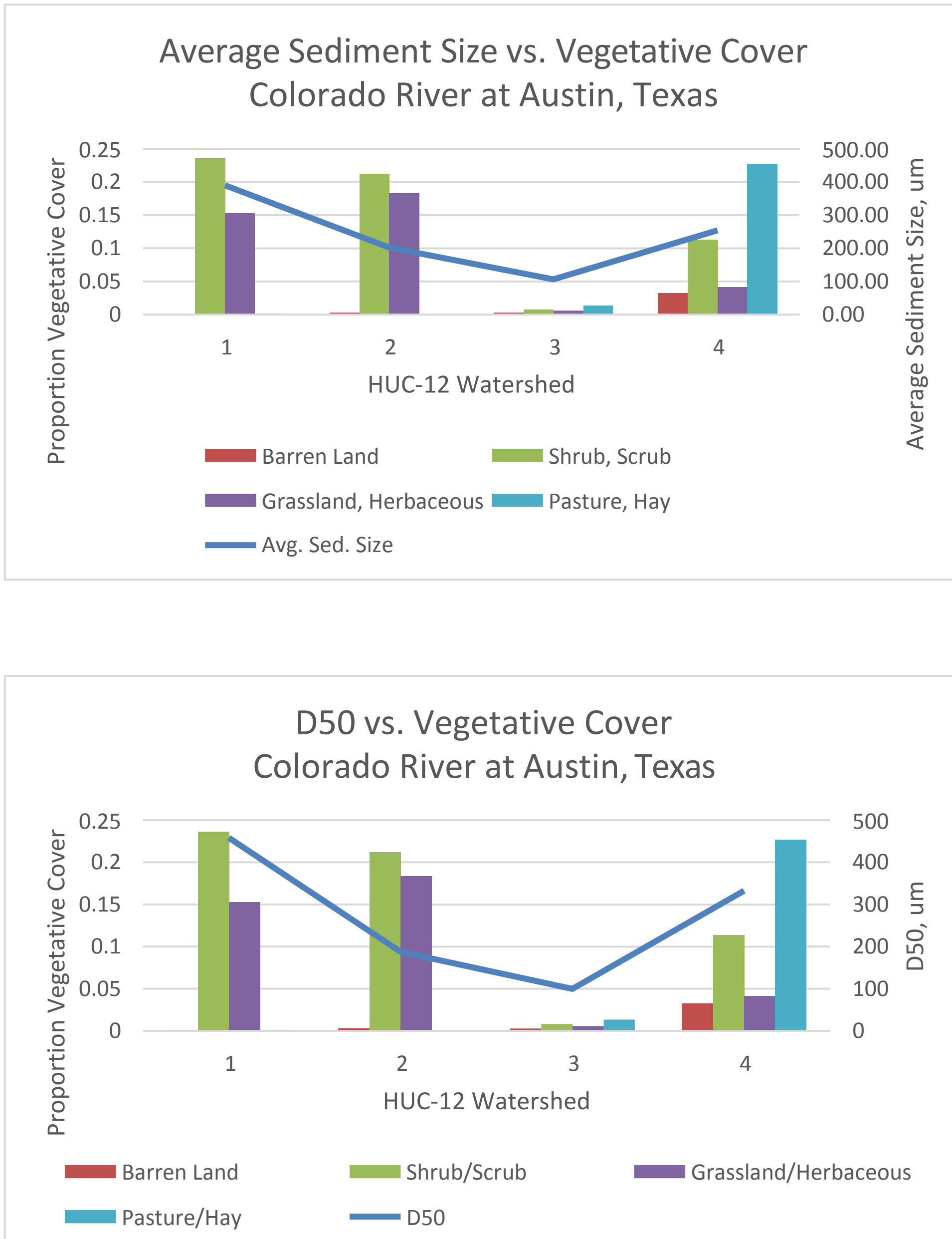
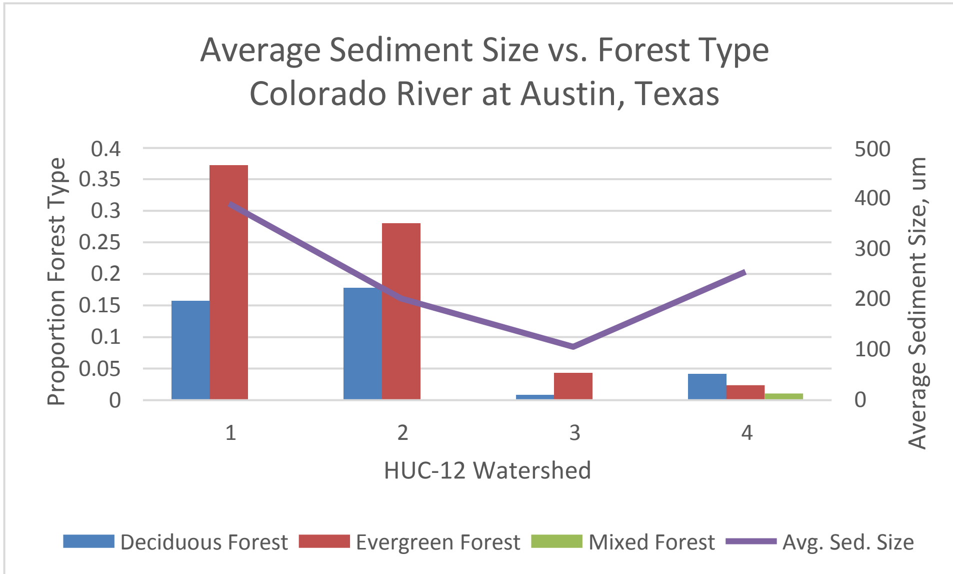


Figure 56: Comparison of D50 sediment size with vegetative cover at the Colorado River near Austin, Texas.



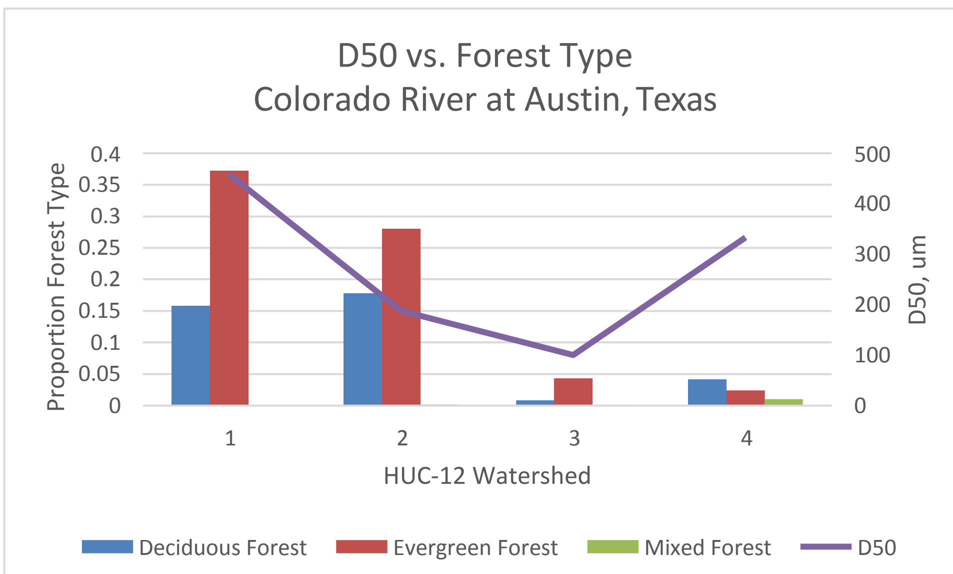
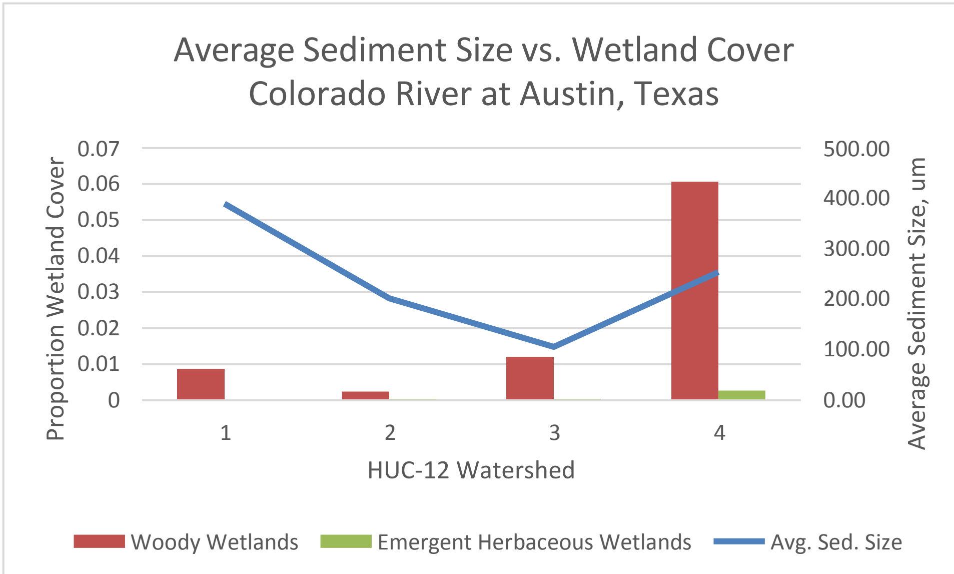


Figure 57: Comparison of sediment size and forest type at the Colorado River near Austin, Texas



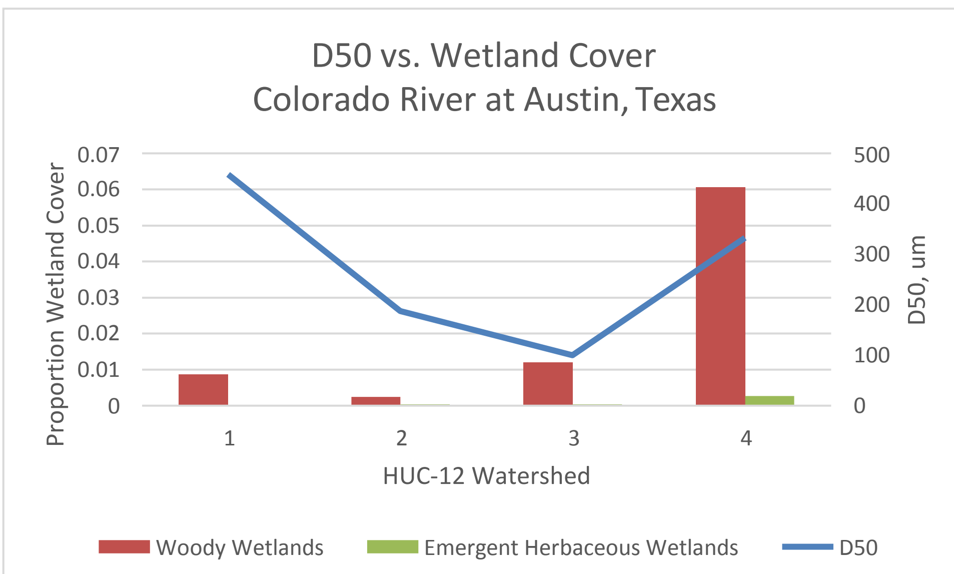
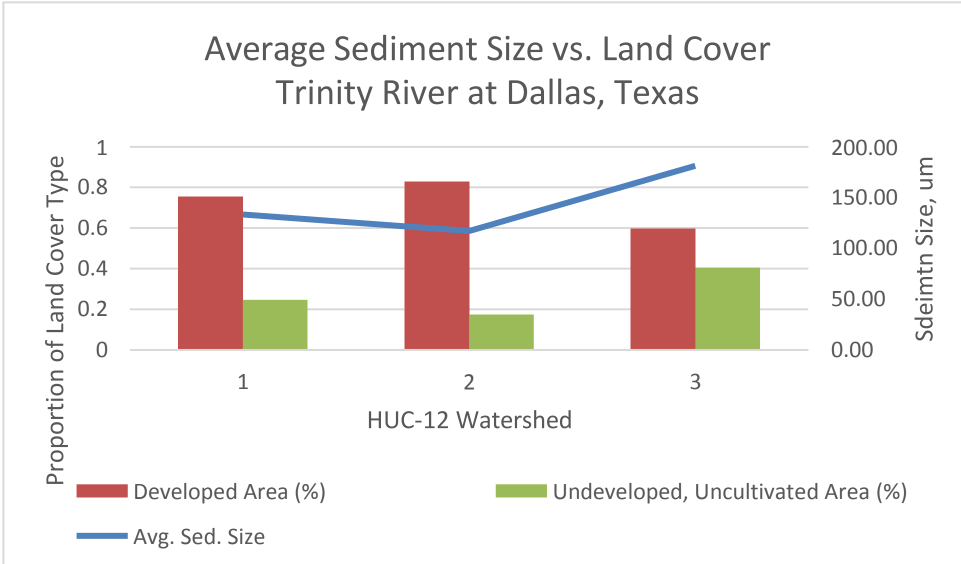


Figure 58: Comparison of average sediment size with wetland cover, Colorado River near Austin, Texas.

Comparisons of sediment size to type of land cover on the Trinity River near Dallas are presented in Figure 59-62.



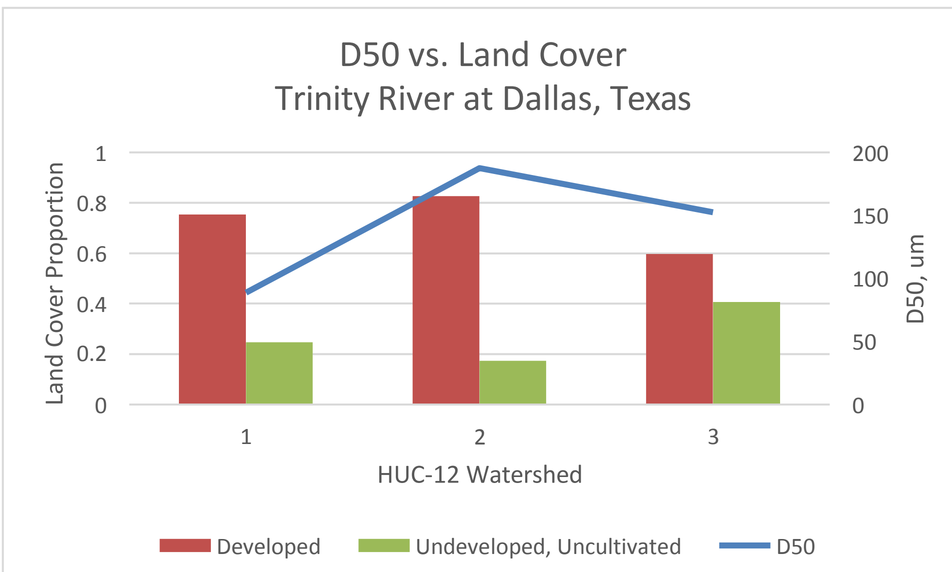
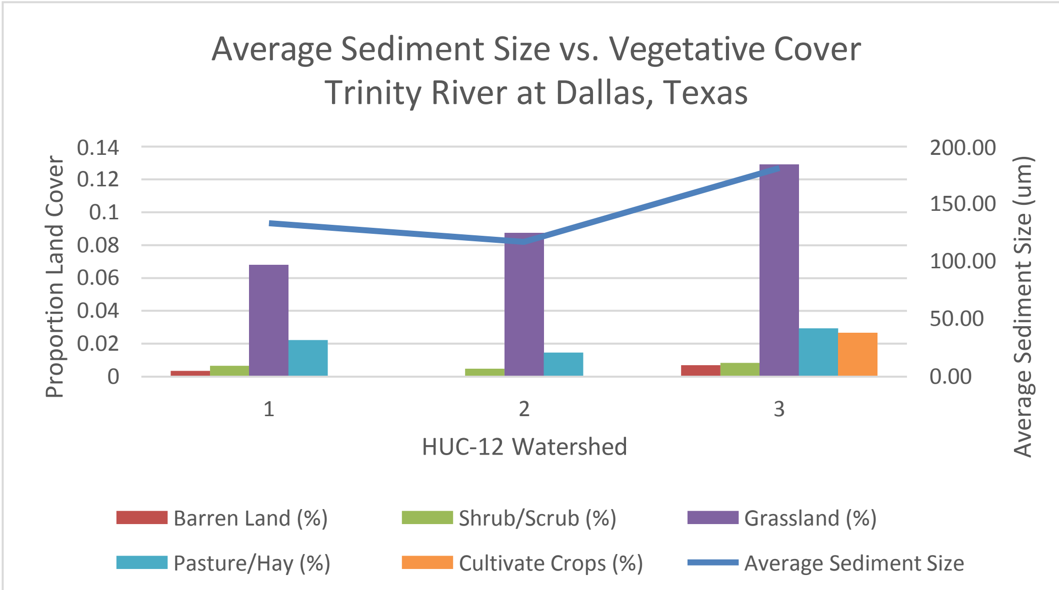


Figure 59: Comparison of sediment size and land cover at the Trinity River near Dallas, Texas.



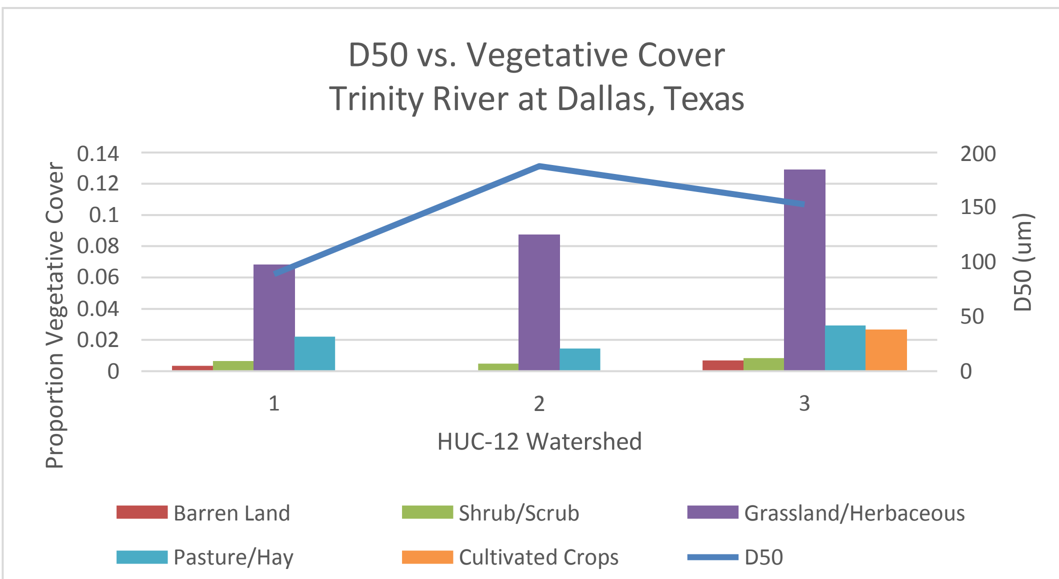
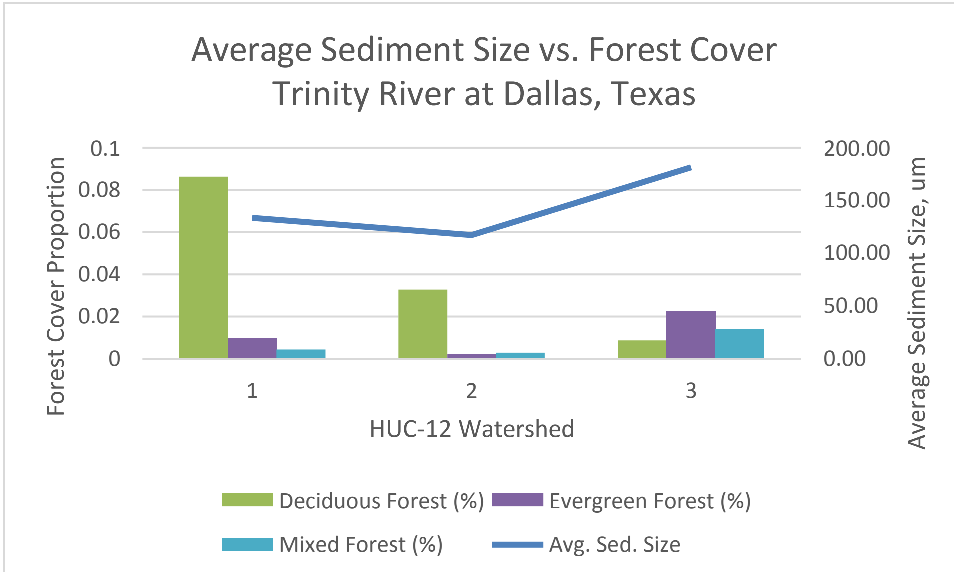


Figure 60: Comparison of sediment size and vegetative cover at the Trinity River near Dallas, Texas.



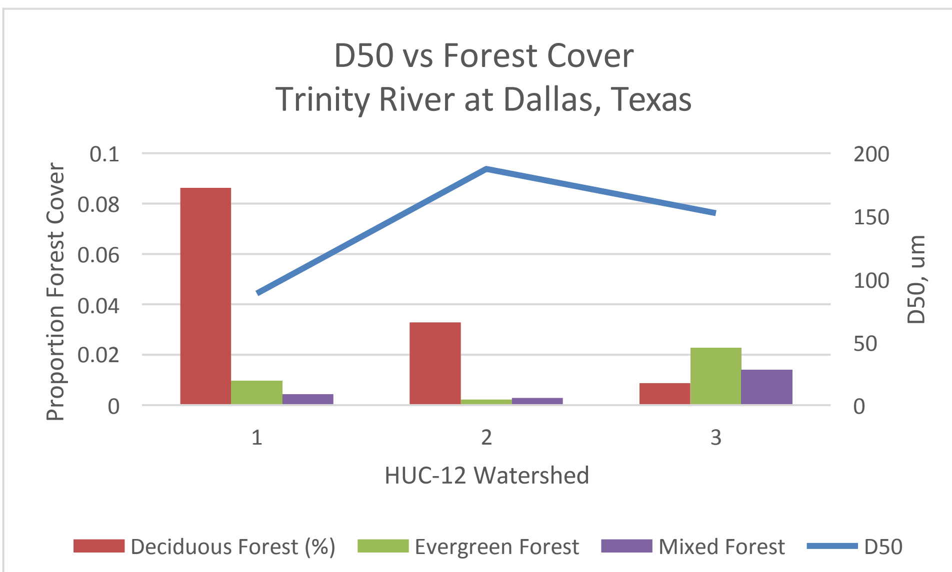
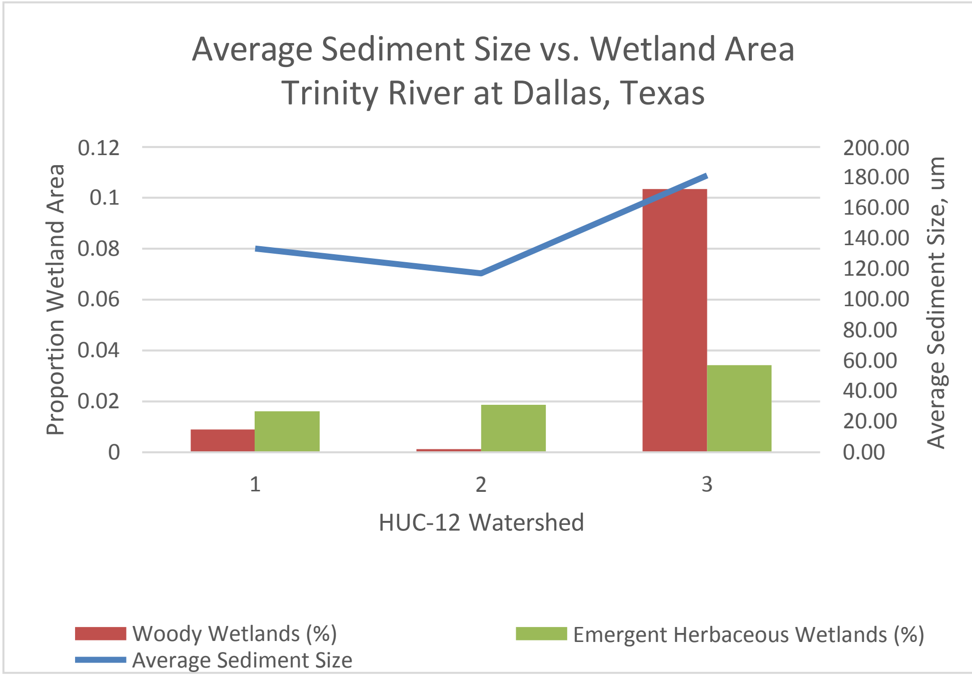


Figure 61: Comparison of sediment size and forest cover at the Trinity River near Dallas, Texas.



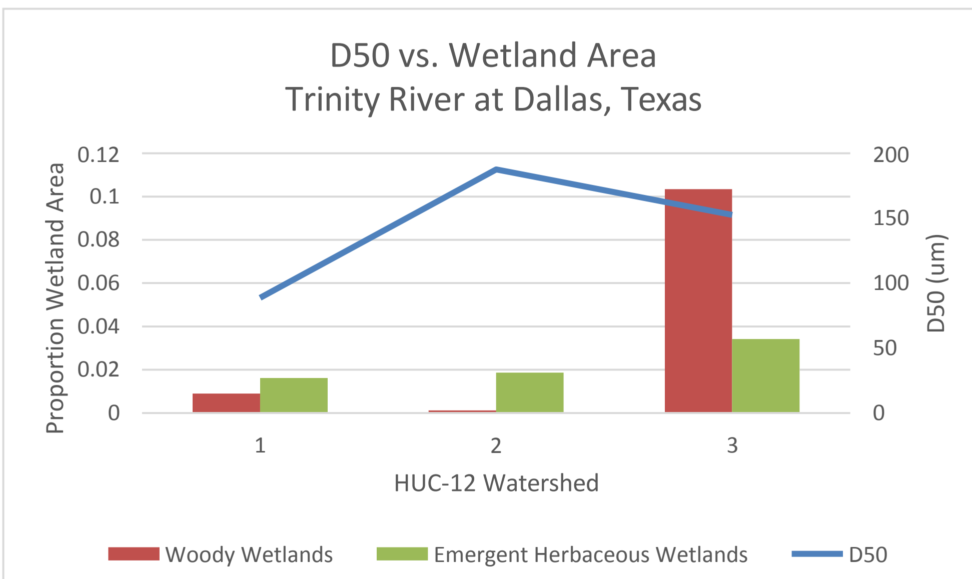


Figure 62: Comparison of average sediment size and wetland area in the Trinity River near Dallas, Texas.

4.2.5 Comparison of Land Cover and Maximum Discharge

Maximum discharge for each study reach was calculated using the Rational method. This method relates peak discharge (q_p, ft^3/sec) to drainage area (A, acres), rainfall intensity (i, in./hr) and runoff coefficient (C):

$$Q_p = CiA$$

Rainfall intensity values came from USGS rainfall intensity-duration-frequency curves for Texas (Asquith, 1998). Area was determined from ArcGIS data of each subwatershed. C values were calculated as a weighted average of each type of land cover for each subwatershed, based on C values given by Margulis (2017). These data were calculated for watersheds upstream of, within, and downstream of urbanization. Results are presented in Figure 63, and a comparison of maximum discharge to developed area is presented in Figure 64.

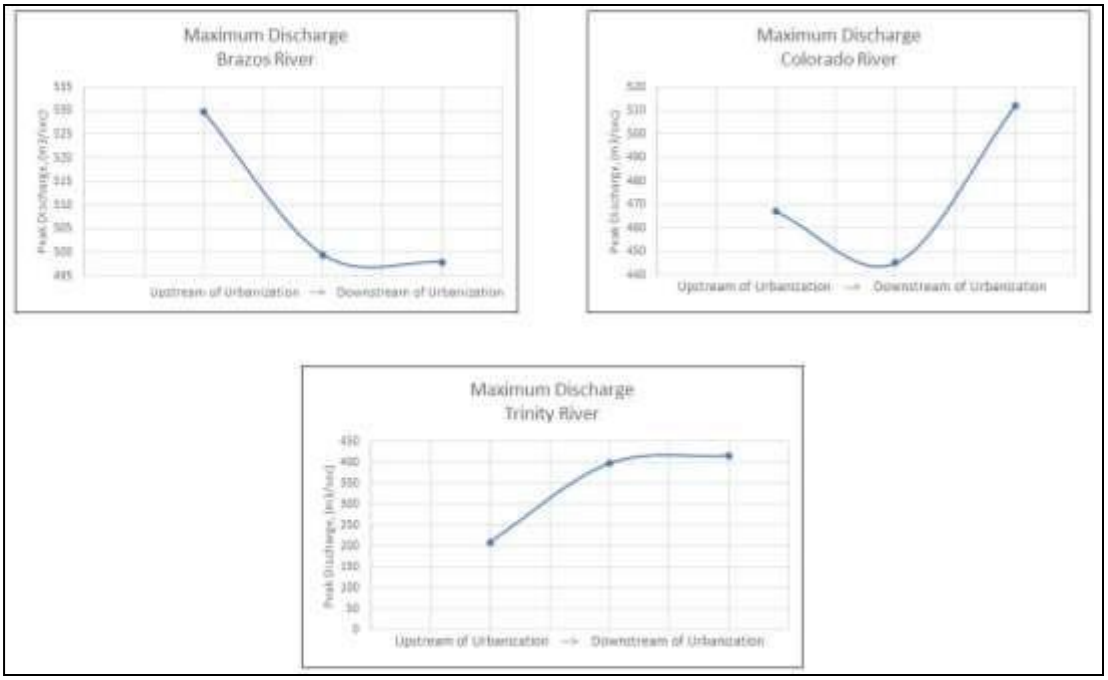


Figure 63: Maximum discharge values from upstream to downstream of urban centers on each of the three studied rivers.

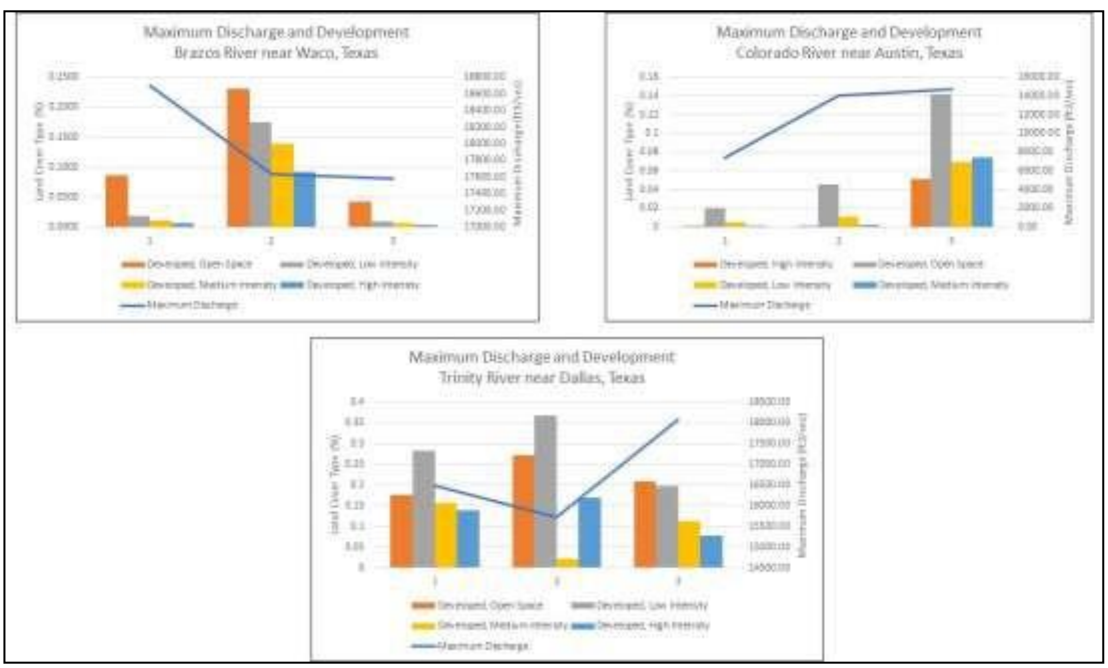


Figure 64: Maximum discharge and developed area

4.3 Discussion and Conclusion

The three rivers investigated in this study present different LULC opportunities. In the Brazos River near Waco, the watershed upstream of urbanization is dominated by rural and agricultural LULC, especially grassland and pasture. The river in this region is highly unmodified, except for occasional public boat ramps and stairs leading to private floating docks. As the Brazos flows through Waco, low intensity development and developed open space (sports fields, playgrounds, greenbelt space) becomes dominant and the river is slowed and widened by an extensive weir downstream of Baylor University. Downstream of Waco, agriculture again dominates as cultivated crops, grasslands, and pasture return as the main land cover types.

The Colorado River near Austin flows from an unmodified channel near Spicewood, Texas, through increasing channel modification until development reaches its maximum within Austin, Texas. Here, the watershed hosts medium to high levels of development, and the channel is stabilized with permeable and impermeable features, including Longhorn Dam. Downstream, land cover in the watershed evolves to low intensity development with grasslands and forest cover. The channel has been influenced by the most modification of the three rivers in this study by the time it is downstream of its respective urban center and is heavily controlled by hydroelectric and flood control dams. Flows downstream of Austin are flashy because of hydroelectric dam operations, although high and low flows may be fairly cyclical.

The Trinity River near Dallas originates at the confluence of two creeks which are already in medium to highly developed watersheds, although grasslands and native vegetation are maintained in developed open spaces. Like the Colorado River, the Trinity River flows through heavy development at its urban center. Unlike the Colorado, the Trinity has no dams or weirs at this stretch. Downstream of Dallas, the channel immediately flows through a protected forest, the Great Trinity Forest.

Type of land cover did not have a discernible effect on average sediment size or maximum runoff in these study reaches. Future research should be conducted on a longer reach of each river, perhaps assessing the entire river catchment. It is likely that the sample areas in this study were not large enough to determine relationships between land cover and sediment size or discharge. This study demonstrates that for small catchment areas, land cover of the immediate sub-watershed does not have a discernable effect on sediment size or discharge. It is important to consider in planning, then, the alteration of land cover throughout the catchment area beyond the immediate sub-watershed. A more complete study will also assess meteorological data for the city centers and surrounding areas to determine possible effects of the urban heat island. For future research, each river will be undertaken as a separate case study and the entire watershed and meteorological data assessed.

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CHAPTER V

CLASSIFICATION SYSTEM FOR RIVERS IN THE TEXAS COASTAL PLAIN

5.1 Introduction

For over a century, researchers have worked to create a useful method of classifying streams. Currently, no single classification provides a comprehensive characterization of Coastal Plain river systems in Texas (Hudson and Heitmuller, 2008). This work seeks to expound upon successful classification schemes already in use to make them more applicable to the low-gradient rivers of the Coastal Plain. Researchers have sought to formally classify rivers since the late 19th century and recently, heightened availability of data and advanced technology for the average user makes diagnostic characterization of river channels and indeed, entire drainage systems, more accessible than ever before. I will review the history of contributions to the classification of rivers and focus on those most commonly in use today, specifically the Rosgen classification system for natural rivers (Rosgen, 1994, 2009). Its advantages and drawbacks are addressed, specifically the oft-cited concern regarding uniformly determining bankfull stage of a river channel. I propose a modification of Rosgen's system which I believe is more easily and accurately implemented on low-gradient rivers and which I believe will remove considerable amounts of observer bias and data variability in diagnostic channel features.

5.1.1 Classification Systems

As the axiom goes, what initially appears complex in river studies is often even more so under further investigation (Rosgen, 1994). Accordingly, formal and informal investigators of the fluvial system have long sought to fashion a classification system of rivers which might provide a starting point for predicting the adjustment of rivers and planning river management. Davis first classified rivers as antecedent, superposed, consequent, and subsequent (Davis, 1890) and then divided rivers into three classes based on relative stage of development: youthful, mature, and old (Davis, 1899, cited in Rosgen, 1994). Zernitz (1932) later defined drainage patterns as dendritic, radial, rectangular, or trellis. The idea of stream order was promoted by Horton (1945) and later by Strahler (1957). In this system, the river network is divided into links between channel heads and tributary junctions and the links are numbered according to the relationship with other stream reaches. First-order reaches, for example, are found nearest the headwaters of the river; second-order at the confluence of two first-order reaches, and so on. Classification systems based upon stream order, like that of Strahler, are likely the most widely used (Buffington, et al.). Strahler (1952, 1956) also introduced a more quantitative, process-based approach to stream classification and watershed geomorphology. Meanwhile, Leopold and Wolman (1957) introduced to the United States Geological Survey (USGS) a classification of streams into straight, meandering, and braided categories. Melton (1936) proposed a classification system based on observable floodplain features. This system considered the shape of the channel and nature of bars and terraces, important features for characterization of low-gradient rivers. Schumm (1963) offered a tentative classification of alluvial rivers which utilized the data available at the time, and based on discharge, channel stability, mode of sediment transport (bed load or suspended load). Thornbury (1969) developed a classification based on valley shape. Keeping up with advances in technology, Culbertson et al. (1967), Kellerhals et al. (1976) and Mollard (1973) developed descriptive classification schemes which could be applied to aerial photography. Schumm (1977) introduced a more process-based approach to dividing rivers into sediment production, transfer, and deposition zones (Buffington, et al.). Later, Buffington and Montgomery (1997) used Schumm's approach to classify mountain rivers into source, transport, and response reaches (Buffington, et al.). Their classification scheme included seven types of channel reaches, based on overall geometry. Brussock et al. (1985) proposed a system for classifying lotic habitats based on three different channel settings (cobble and boulder bed, gravel bed, or sand bed) and three physical factors (relief, lithology, and runoff) which control all other interacting parameters. Eze and Knight (2018) take a more process-based view and consider the stability of the overall channel and future trajectory in their proposed classification system.

Whereas the aforementioned systems of classification are intended as general schemes of classification for all rivers, others address a specific niche. In their assessment of segments of a bedrock channel in South Africa, for example, Heritage et al. (2001) developed a classification system based on morphological units and various quantitative data: regional slope, low-flow slope, calibrated energy slope, mean annual sediment yield, runoff, and sediment transport. Others have focused on the low-gradient alluvial rivers such as are typical in this study area. Melton (1936), for example, proposed a classification system based on observable floodplain features. This system considers the shape of the channel and nature of bars and terraces, important features for characterization of low-gradient rivers. Schumm (1963) offered a tentative classification of alluvial rivers utilizing the data available at the time, and based on discharge, channel stability, mode of sediment transport (bed load or suspended load), and Thornbury (1969) developed a classification based on valley shape. Rust (1977) proposed a classification of alluvial systems based on the number of braids per mean meander wavelength. Alluvial rivers have characteristic floodplains, classified by Nanson and Croke (1992) into three classes based on energy level and cohesiveness of sediment.

4.1.2 Popular Classification Systems in Use Today

Today, the Rosgen system for the classification of rivers (1994) has become the most dominant approach among practicing scientists and engineers in the United States, whereas the Strahler system is more used by the USGS (Wan, et al., 2013). Tadaki, et al. (2014) provided an overview of other recent developments in river classification; their work highlights four high profile classification systems that have been put into practice around the world, each adapted and applied to a different purpose. Rosgen's system, for example, is particularly useful for those involved in restoration efforts. The River Habitat Survey is used in the United Kingdom and elsewhere to "provide an objective basis for determining the physical character or rivers which could then be used to derive a scheme for assessing habitat quality" (Tadaki, et al.). This system was developed during the 1990s by environmental agencies in Europe, and rather than acting as a traditional classification scheme, it serves as a database for morphological characteristics. Though it is a highly qualitative approach to river studies, its sampling does make it statistically useful to the environmental scientist. Internationally, Systematic Conservation Planning is used as an "*evaluative classification inventory*" (Tadaki, et al.) to prioritize conservation efforts by modeling the natural causes of anthropogenic conservation efforts. The objective of Systematic Conservation Planning is to rank streams (or other natural features) according to their value for conservation or other objectives. Variables contributing to this objective are established and recorded for the stream of interest, and models of these variables under different scenarios are created. Based on the outcomes of these models, streams or stream reaches are classified based upon the potential for conservation. In Australia, the River Styles Framework is used. This system has two levels of classification: geomorphic "units" and the interrelationships of the processes are established primarily, followed by the designation of a "tree" of rivers based on catchment or localized interpretation of specific processes. (Tadaki, et al.) In the United States, a system called Natural Channel Design was established in the 1990s as a method of classifying rivers so that human intervention could be prescribed which would return the river to its "natural" state. This is the system of classification that Rosgen and his own system of classification belongs.

As Tadaki et al. states, "River classification provides an abstraction of what would otherwise be an inconceivable array of natural variation into relatively few selected parameters whether they be quantitative, qualitative, or both." (2014). It is necessary that this "inconceivable array" of variation be classified by those who wish to study, restore, and protect the rivers so that the job of doing so might be approached as a qualitative endeavor. All existing classification systems, however, have shortcomings with respect to such qualification need.

4.1.3 Critiques of Classification Systems

As indicated by Tadaki, et al. (2014), river classification cannot cover all details of any fluvial environment. Therefore, some information must be overlooked, or a new subcategory of classification would be required for each new situation at any time. Although any river can be made to fit into a certain classification scheme, this does not mean that all its relevant relationships or processes are accounted for. (Tadaki, et al. 2014)

The existing classifications ignore the complexities inherent in natural systems. This oversimplification is problematic because it may lead to misapplication of efforts prescribed by a classification system, as well as extension of the classification system beyond its original intent (Juracek and Fitzpatrick, 2003). As Juracek and Fitzpatrick (2003) observe, stream channels are especially dynamic and generally in a state of adjusting to the environment. Therefore, the present conditions do not necessarily reflect former, long term, or future conditions. This natural variability, even within a single stream channel, has been a foremost factor in preventing the development of an ideal geomorphic classification of streams (Juracek and Fitzpatrick, 2014).

According to Juracek and Fitzpatrick (2014), an ideal geomorphic classification system would be process-based. In other words, the river should be considered as a combination of different processes at work in it, not merely the current morphological appearance. This allows for acknowledgment of and planning for the changes to the river that are occurring currently and will continue in the future, allowing the system to be applicable over a wide range of spatial and temporal scales. It would be advantageous for the system to include a historical perspective of the river, documenting previous channel conditions to better understand the stability of the current channel conditions. Their assertion is not without precedent. Frissell et al. (1986) suggested that a useful stream classification system must be based on a conceptual view of how stream systems are organized in space and how they change through time. They proposed a hierarchal classification system in which a system at one level forms the environments of its subsystems at lower levels. Similar hierarchal classification systems are proposed by Van Niekerk et al. (1995) and Rowntree and Wadeson (1996).

4.1.4 The Rosgen System

The Rosgen classification system has become the system most commonly used by scientists and engineers (Wan, et al., 2013), in part for its ease of application. Developers of classification schemes commonly describe the process by which streams should be classified and what features should be emphasized, but few offer an easy-to-use, numerically based flowchart to allow ease of classification by researchers and entry-level technicians alike. Ease of implementation is fundamental for a classification system to be widely accepted and used, not esoterically discussed and set aside.

Rosgen’s classification includes four levels of hierarchal classification. The first level characterizes the broad morphological properties of the river, including landforms, climate, and basin-wide characteristics. This level then gives way to morphological descriptions of channel-level characteristics such as patterns, entrenchment ratios, sinuosity, etc. The next level addresses the stability of the stream as determined by riparian vegetation, bank erodibility, as well as depositional and meander patterns, and the fourth level involves direct measurements of sediment transport, rates of bank erosion, and various biological data for reach-specific characterization (Rosgen, 1994). Whereas the Rosgen classification system is hierarchal, Mosley (1987) recommends a river classification system which operates "bottom-up", classifying rivers based upon the component parts. Top-down river classification hierarchies, in which a system at one level forms the environment for the subsystems below it, are widely accepted but have proven difficult in some rivers because of the complex interactions within the catchment (Mosley, 1987).

4.1.5 Determining Bankfull Stage

In the Rosgen method, width/depth ratios are based on cross-sections based on the width of the bankfull surface divided by the mean depth of bankfull width. Entrenchment ratio is a measure of vertical containment by a ratio of the width of the flood-prone area divided by the bankfull width (Rosgen, 2009). Usage of values for bankfull stage for characterization differs from the Culbertson, et al. (1969) method of classifying alluvial rivers, which uses normal discharge. Bankfull discharge represents a distinct morphological discontinuity between in-bank and overbank flows (Charlton, 2015). Additionally, Harvey (1969) notes that in alluvial channels, bankfull conditions correspond to maximum stream competence and Carling (1988) finds that in alluvial rivers, channel capacity is maintained at bankfull discharge. Its usage as a diagnostic tool likely stems from work by Leopold and Maddock (1953) which demonstrated that bankfull discharge marks a threshold above which relationships between discharge and sediment transport differ from those below bankfull. In subsequent studies, Leopold and Wolman (1957) suggested that the channel cross-section accommodates a discharge that recurs in a predictable time period, and that bankfull discharge has a return period of one to two years. Similar recurrence intervals were reported in separate studies by Dury (1961a), Brush (1961), and Leopold, et al. (1964). This makes bankfull stage a good indicator of regional channel characteristics.

The concept of bankfull was developed in high-gradient Piedmont and montane river systems (Leopold et al., 1964; Hupp, 2000) and has drawn criticism from some practitioners (J. Giardino, 2018, personal communication) who find bankfull stage difficult to determine in low-gradient rivers. The usage of bankfull stage does, however, offer the advantage of uniformity of measurement standard. Normal discharge is difficult to determine in rivers which are altered by hydroelectric dams, weirs, and associated management practices. Its consideration may offer insight to the stability and flow characteristics of the specific stream reach, but will not reveal the structure of the overall channel. Bankfull elevation and width, when accurately determined, will remain constant far longer than normal discharge levels, thus, allowing for monitoring and prediction of channel adjustment over temporal scales.

Still, usage of bankfull measurements are not without controversy. The concept of a universal return period for bankfull discharge is challenged, and may even vary along the same river (Pickup and Warner, 1976; Williams, 1978; Castro and Jackson, 2001). Castro and Jackson (2001) found that recurrence interval for bankfull flows vary considerably by climate. Determination of bankfull discharge in the field has also proven problematic. At cross-sectional scale, local physical channel characteristics interact to produce a non-obvious progression from the main-channel banks to the floodplain (Navratil et al., 2006). Recommendations for identifying bankfull stage may be based on geomorphological indicators or quantitative analysis, as demonstrated in Table 16.

Author	Method for Determining Bankfull	Indicators or Analysis
Dury, 1961b	Geomorphological Indicators	-Level equal to the elevation of the floodplain -Level just below overbank stage. *Overbank defined as:* -Exceeding height of natural floodplain -Exceeding height of horizontal outer parts of floodplains with natural levees bordering channel -Exceeding average height of floodplain with natural levees -Permitting spill over lower parts of natural levees -Permitting spill over artificial banks -Spilling water begins to damage property
Leopold, et al. (1964)	Geomorphological Indicators	Height of adjacent floodplain
Harvey, 1969	Geomorphological Indicators	Elevation in natural stream channel above which spilling onto the floodplain occurs.
Harrelson, 1994	Geomorphological Indicators	-Top of point bar -Lower limit of perennial vegetation -Slope break along bank -Change in particle size -Undercuts in the bank -Stain lines or lower extent of lichens on boulders
Wolman, 1955	Quantitative Analysis	Lowest value of width-to-depth ratio as determined from graph of width-to-depth ratio plotted against stage.
Nixon et al., 1959	Quantitative Analysis	Empirical equations
Richards (1982) Rivers. Form and Process in Alluvial Channels	Quantitative Analysis	Equivalent to most probable annual flood, with one-year return period.
Riley, 1972	Quantitative Analysis	Bench Index
Williams, 1978	Quantitative Analysis	Empirical equations
Carling, 1988	Quantitative Analysis	Geometric reconstruction
Tayfur and Singh, 2010	Quantitative Analysis	Empirical equations

Table 16: Definitions of bankfull stage and proposed procedures for its determination.

A hurdle of implementing bankfull considerations in low-gradient rivers, like those in the Coastal Plain, has historically been the difficulty of simply determining bankfull stage. Roper et al. (2008) demonstrate that difficulties in determining bankfull stage can render Rosgen classification unreliable, as even minor discrepancies in bankfull assignment result in drastically variable entrenchment ratios, one of the first classification variables used in the Rosgen system. Meanwhile, variables which are more consistently measured, such as channel slope, are not weighted heavily enough to change classification (Roper et al., 2008)

Difficulty of identifying bankfull stage in Coastal Plains rivers stems from underfit rivers flowing through multiple, terraced floodplains which result from cyclic transgression/regression episodes (Hupp, 2000). In the field, it is exceedingly difficult to determine whether the top of a given bank indeed coincides with the adjacent main floodplain or whether it marks elevation of an ancient terrace or other minor irregularity. It is possible to easily obtain large-scale representations of channel cross-sections from remote sensing data which can offer clarification on this point. Google Earth Pro®, for example, offers the Path function within its Ruler tab that displays the distance between two points defined by the user and also the elevation profile (Figure 59). Extending the visual limits of the elevation profile allows the viewer to determine what elevation point marks the elevation of the true floodplain, thus determining the bankfull elevation of the river channel.

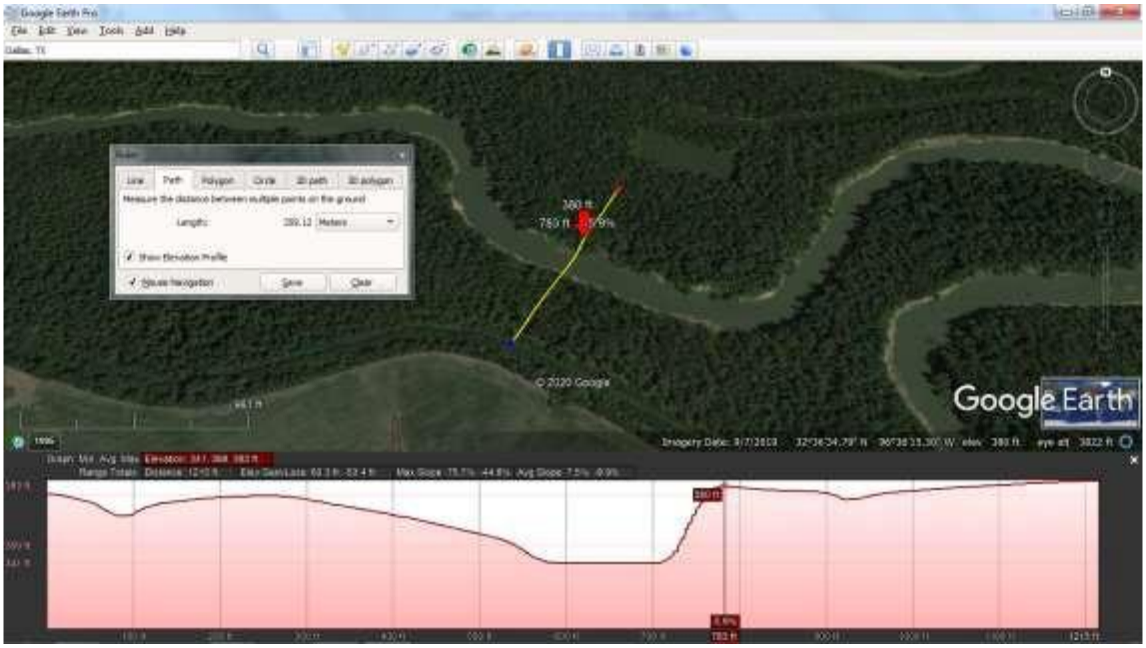

Figure 58: Screenshot of Google Earth (R) imagery of Colorado River near Austin, with the elevation profile displayed. Such tools allow a large-scale view of the river channel which simplifies the process of determining the bankfull stage.

Even this method is not without a margin of error. Different estimations of bankfull stage using this method will still fall within a margin of error which may moderately affect ensuing bankfull calculations but will lead to a wide discrepancy of entrenchment ratios. I, thus, recommend that entrenchment ratio should not be a primary variable in classification of Coastal Plains rivers.

When using a DEM to image the river channel, the lowest channel elevation marks the water surface, not the channel bottom. It is, thus, still necessary to reconstruct the channel before calculating its area. Now, several options exist for doing this entirely from remote sensing data (Smith, 1997; Stumpf et al., 2003; Alsdorf et al., 2007; Marcus and

Fonstad, 2010; Gleason and Smith, 2013; Mersel et al., 2013; Smith and Pavelsky, 2013). Researchers with aptitude in these methods will benefit from implementing them. For those without access to the necessary analysis programs or who may prefer more traditional methods, the area of the bankfull channel is still easily determined using a combination of traditional field techniques and readily available software (Figure 60). Bjerklie (2007) offers simple empirical equations for estimating bankfull velocity and discharge of remotely sensed rivers, which may be used alone or in conjunction with field measurements.

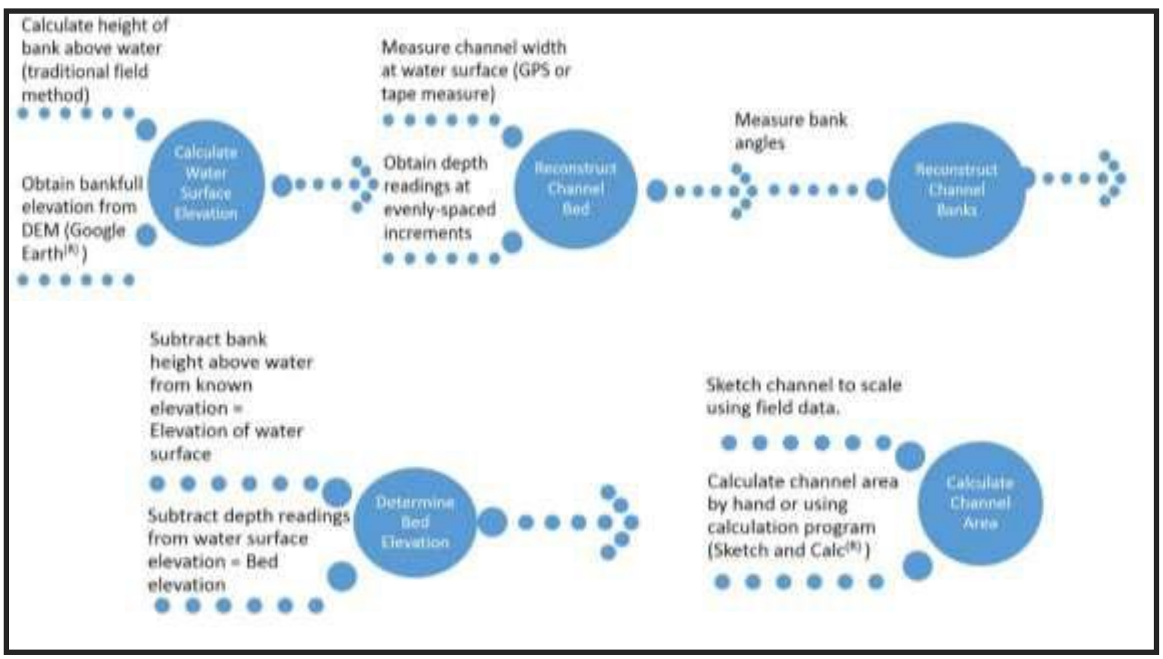

Figure 59: Process for determination of bed elevation and bankfull channel area using a combination of field and simple remote sensing techniques.

Although modern technology has simplified the process of calculating bankfull stage, it remains an imprecise standard in most Coastal Plain Rivers because of the channel shape. Millennia of ancient river terraces now worn to rounded yet wide benches makes definition of bankfull stage challenging in the field and by remote sensing methods. It may, thus, be useful to reimagine bankfull stage as a bankfull zone when studying these rivers.

4.2 Coastal Plain Rivers

The Coastal Plain extends from southeast Texas to New England and is formed predominantly from alluvial and marine sediment deposition from adjacent montane and Piedmont regions since the Mesozoic era (Hupp, 2000). This region is flat and dominated by clay and sand, exposed by regression of Oligocene oceanic transgressions (Phillips and Slattery, 2008).

Streams in the region are generally low-gradient and deficient in clastic sediment, although those originating in higher provinces have high suspended-sediment loads. The substrate in these regions is often unconsolidated or poorly consolidated, offering little resistance for fluvial containment (Phillips and Slattery, 2008). These rivers are dominated by sand or silt bed channels along the entire longitudinal profile, with pools and riffles only occurring in higher gradient regions (Brussock et al., 1985). The rivers flow through self-formed valleys in passive-margin, tectonically stable areas, though may be affected by antecedent topography (Phillips and Slattery, 2008). A strong seasonal variation in discharge occurs on the Coastal Plains, as seasonal variations in evapotranspiration and rainfall produce significantly different hydrologic seasons (Hupp and Osterkamp, 1996; Hupp, 2000; Hudson and Heitmuller, 2008). Low-flows occur from June to October, when streamflow is generally restricted to a meandering main channel, and high-flows occur from November to May, when large parts of bottomlands may be inundated. This creates order of magnitude differences in wetted perimeter, width-depth ratios, and values of roughness on the same reach from season to season (Hupp and Osterkamp, 1996; Hupp, 2000). Hudson and Heitmuller reported on hydrologic data from the USGS for 14 Texas coastal plain rivers draining into the Gulf of Mexico (2008). The rivers range in annual discharge from 258 cm/s to 1,600 cm/s. The drainage areas range in size from 2,210 km^2 to 557,722 km^2 and the lengths range from 146.8 km to 2,895 km. Bankfull discharges range from 30.3 cm^3/s to 335[10] cm^3/s, and peak discharge ranges from 898 cm/s to 13,200 cm/s. The width of each Holocene river valley ranges from .5-125 km. Sinuosity ranges from 1.11-2.48, and floodplain relief ranges from .55 meters to 5.80[11] meters. Alluvial processes of the Coastal Plains rivers develop broad floodplains that support Bottomland Hardwood Forest ecosystems, which in turn interact with hydrologic and fluvial geomorphic processes. Thus, the character of one is influenced by the other (Hupp, 2000).

In the Bottomland Hardwood Forest, two types of streams develop: alluvial rivers that arise in uplands, transporting substantial amounts of eroded sediment, and blackwater rivers that arise fully within the Coastal Plain. The latter transport relatively little fine sediment (Hupp, 2000). Those that arise in uplands or Piedmont regions experience an abrupt reduction in gradient upon crossing into the Coastal Plains, leading to more frequent overbank flows, flatter hydrographs, and longer periods of inundation (Hupp, 2000; Phillips and Slattery, 2008). The complexity of river systems in the Coastal Plains stems from the interaction of entrenchment during marine regressions alternating with filling and widening during transgressions (Hupp, 2000). Today, many of the rivers are underfit, meaning the present channel does not carry sufficient discharge nor sediment to have created the broad alluvial floodplain through which it flows (Hupp, 2000). This condition may stem from loss of drainage area through stream capture, a reduction in rainfall since the end of the Pleistocene Ice Age, or reduction in discharge and sediment load since initial melting of continental glaciers at its end.

Coastal-plains streams are geomorphologically distinct in form and process from medium- and high-gradient streams (Hupp and Osterkamp, 1996). Ashley et al. (1988) and Heritage et al. (2001) indicate that most rivers begin as bedrock-dominated and transition to alluvium-dominated. The standard model for rivers includes mountain headwaters with boulder and cobbled channel structure with little sedimentary structures, as the high flow tends to erase such structures. Coastal Plains rivers, however, lack high-relief areas. This results in a lack of pools and riffles and gravel- or sand-bed headwaters. The usual geomorphic pattern of stream channel succession is, thus, shifted upstream (Brussock et al., 1985)

A subregion of the Coastal Plains, the Gulf Coastal Plains border the Gulf of Mexico (Figure 60). In Texas, the Gulf Coastal Plain is further subdivided to specific phsyiogrpahic regions with diverse geology. As the rivers in this study area are all fully contained within Texas, I will briefly address these regions. The uppermost portion of the Coastal Plain is called the Blackland Prairie. The Blackland Prairie ranges from 150 meters to 350 meters in elevation near San Antonio and Austin, and its width ranges from 25 km near San Antonio to 225 km north of Dallas (Hudson and Heitmuller, 2008).

The topography is gentle rolling hills, and soils are thick and fertile. This region contains headwaters for major tributaries over 2,500 km^2 in area for some of the largest coastal watersheds. The next, and largest, segment of the Coastal Plain is the Interior Coastal Plain, which ranges in elevation from 90-250 meters. As the geology of the Interior Coastal Plain varies from resistant sandstones to nonresistant shales, the topography contains elongated hills and low plains and valleys. Many watersheds of various sizes are in the Interior Coastal Plains, as well as headwaters of some intermediate river systems. The youngest region of the Coastal Plain is the Coastal Prairie. Though it appears flat, bedrock here dips gently to the southeast. Elevations in the Coastal Prairie range from 90 meters to sea level. The most prominent force altering rivers in this region has been fluctuation of sea level, leading to incision and coastal advance and retreat (Hudson and Heitmuller, 2008). Major geophysical threats for the Coastal Prairie are land subsidence, natural and human-induced; through urbanization and accelerated groundwater withdrawal. Subsidence is altering the nature of rivers in the region, and floods have become slightly more frequent and impactful. Because of its low elevation and poor drainage, this region of the Gulf Coastal Plain is particularly sensitive to the effects of climate change and rise in sea level.

River basins in Texas, in general, are impacted by various precipitation events. As Texas rivers ultimately flow into the Gulf Coastal Plain before emptying into the Gulf of Mexico, these precipitation events will impact the rivers of this study, even if the headwaters are distributed in different physiographic regions. Tropical disturbances such as hurricanes, tropical storms, and tropical depressions are semi-annual events, particularly during the months of June through late October and November. Fronts migrate over the state commonly during the fall and winter, and bring with them extended periods of rainfall, followed by an often dry summer season. Thunderstorms normally occur in summer, which brings sudden influx of high amount of precipitation as a compensation to the summer dryness. Finally, the migration of the subtropical jet stream across the state brings with it anomalous weather patterns.

4.3 Classification Scheme for Coastal Plains Rivers

I propose a classification scheme based upon reliably determined river characteristics for low-gradient rivers such as those of the Coastal Plains. Bankfull stage is still utilized, because it offers a uniform reference point for evaluation of channel shape and can be reasonably ascertained from remote images. Entrenchment ratio, however, is not utilized. Further, the concept of bankfull stage should be reconsidered as a bankfull zone. This allows for recognition of the difficulty of precise identification of bankfull stage of low gradient Coastal Plains Rivers even by experienced practitioners and reduces error in ensuing calculations based upon the characteristics of bankfull level.

I do not attempt to dismantle Rosgen's system of classification, but to make it more useful to those studying low gradient Coastal Plains Rivers by utilizing as diagnostic properties physical features which are most readily observable and quantifiable in the field and using remote sensing data. This classification system also considers anthropogenic modification to the channel and watershed, as this imposes strong influence on the nature of river processes. The classification scheme is based on three levels, representing channel material, anthropogenic modification, and channel characteristics. The first and most broad level is based on channel material: bedrock, boulder, cobble, gravel, sand, or silt/clay. The second level is based on level of anthropogenic modification, as determined by Key 1. The third level considers more detailed channel characteristics, beginning with width to depth ratio within the bankfull zone. Bankfull zone is defined here as the region extending from the threshold of the main channel and the adjacent step sufficiently wide to sustain permanent structures to the threshold of the main floodplain (Figure 61). After calculation of W/D ratio in the bankfull zone, rivers are further classified by sinuosity, and finally by channel slope.

Figure 60: Example of bankfull zone: region extending from threshold of main channel and step wide enough to sustain permanent structures, and the threshold of the main floodplain.

Bankfull zone, in most favorable conditions, will narrow to the ideal bankfull stage described by previous authors, and allows a margin of error for less favorable morphological conditions. Figure 62 shows Key 1, to be used for assessment of anthropogenic modification of a river channel. Each category is considered for the river reach being studied and the best descriptor selected. Each row of options is given a point value, indicated in the far left column. After all categories are considered, points per row are tallied and recorded in the far-right column. Total points in this column are counted and used as the overall modification score in Key 2 (Figure 63). Figures 64-69 provide detailed breakdown of the classification system, subdivided by channel material. Figures 62 and 63 offer a more concise checklist and key which will be simpler for use in the field.

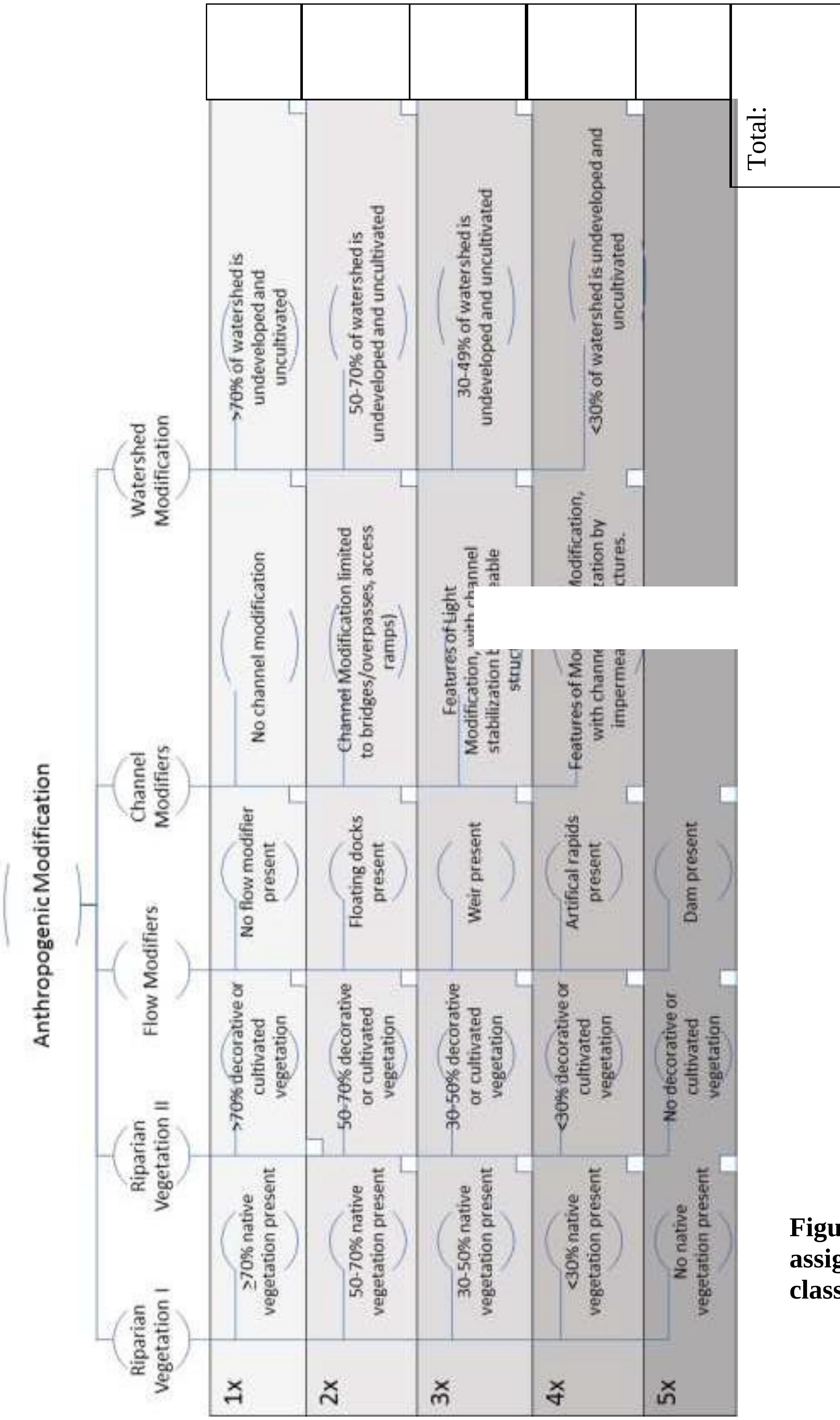

Figure 61: Key 1 for assignment of stream classification.

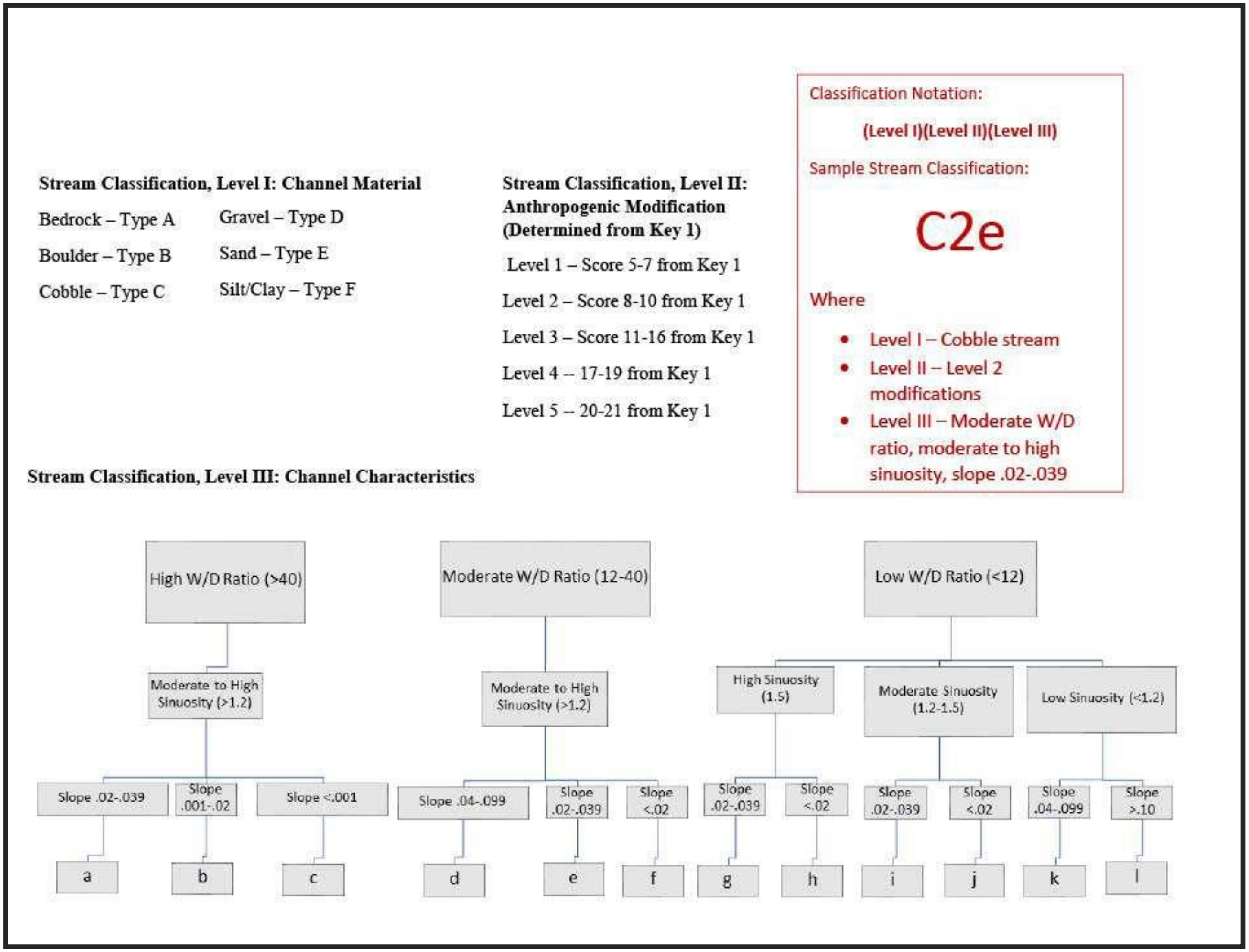

Figure 62: Key 2 for assignment of stream classification.

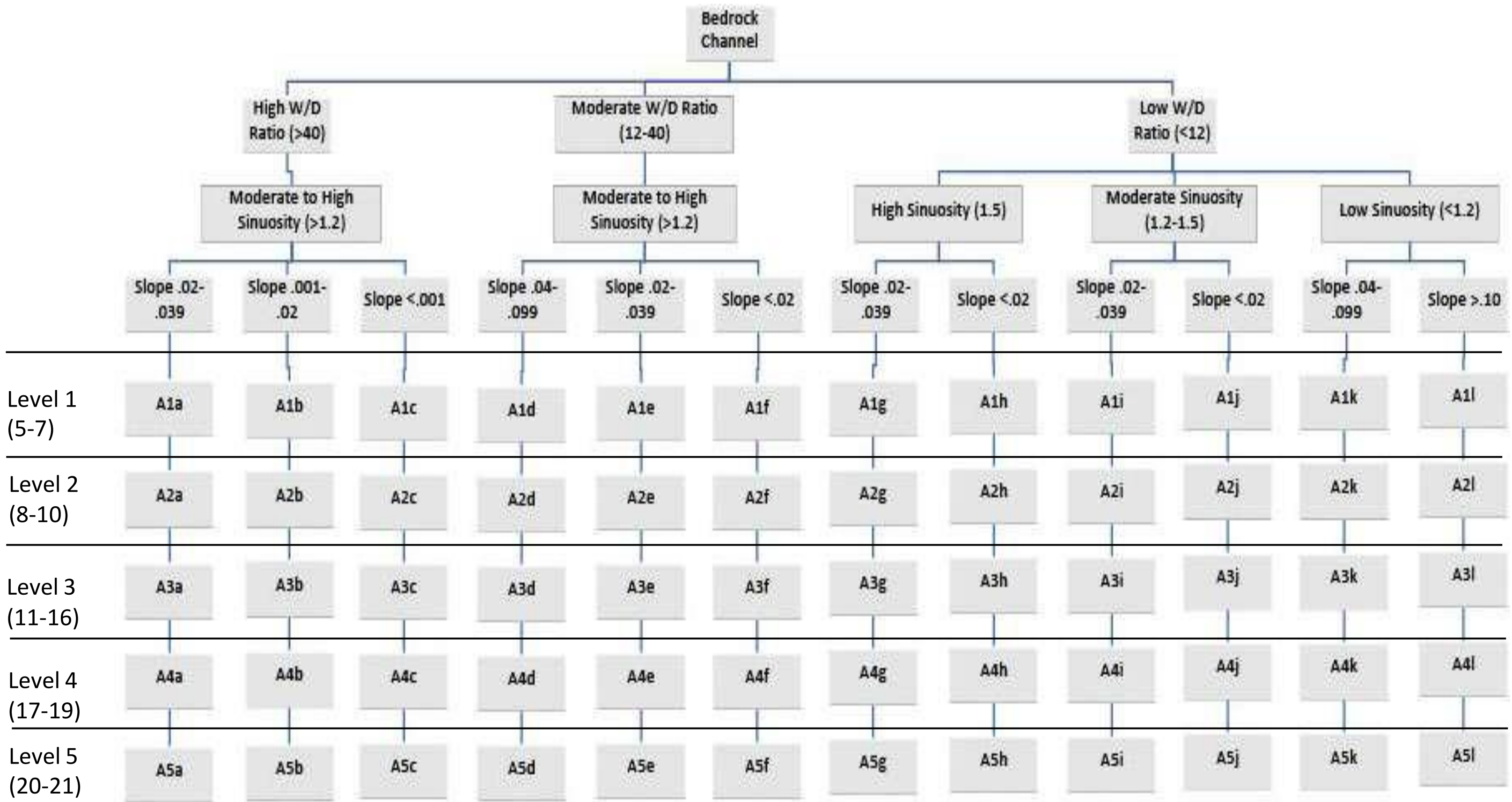

Figure 63: Detailed classification key for bedrock (Type A) channels

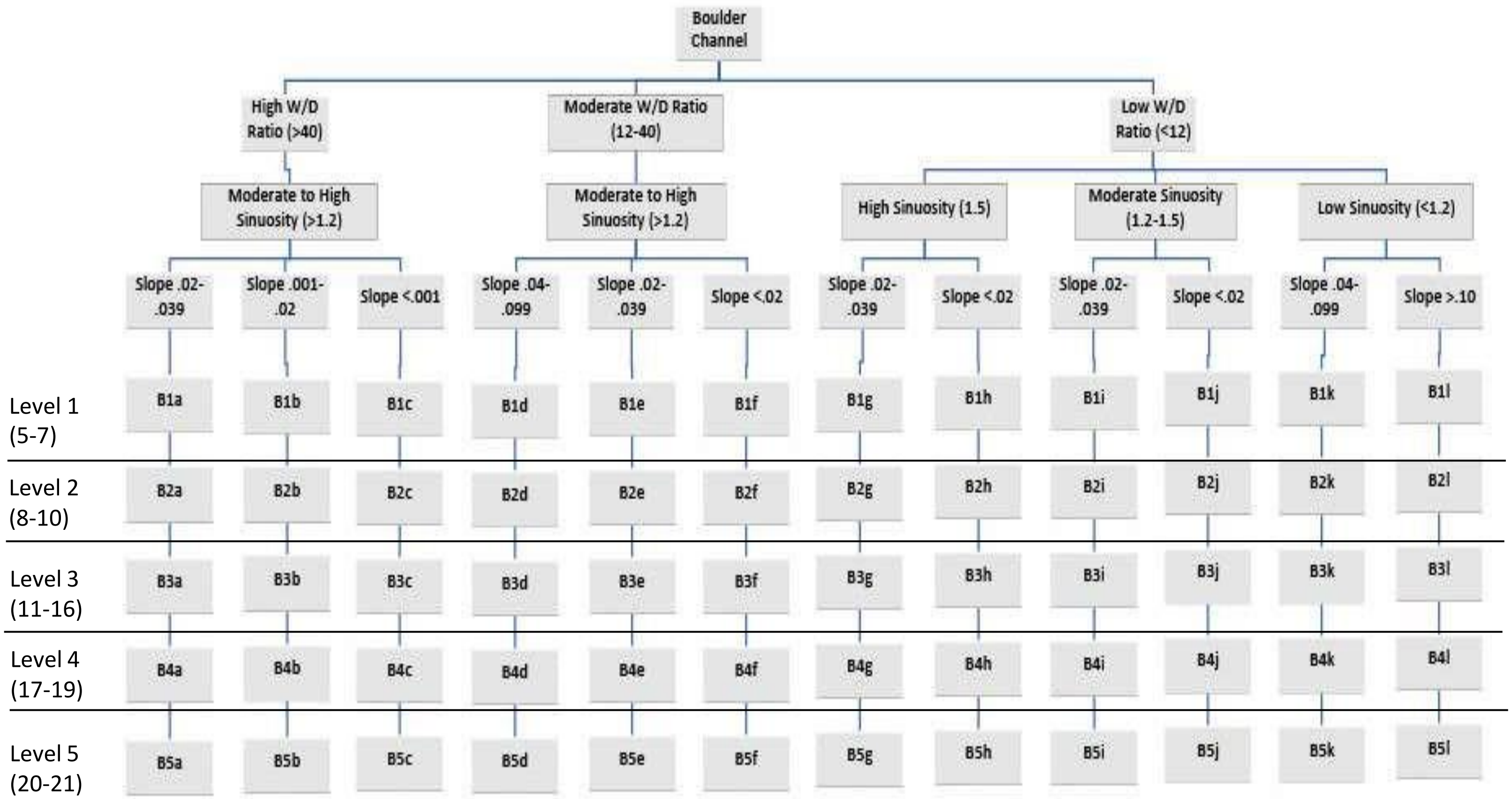

Figure 64: Detailed classification key for boulder (Type B) channels.

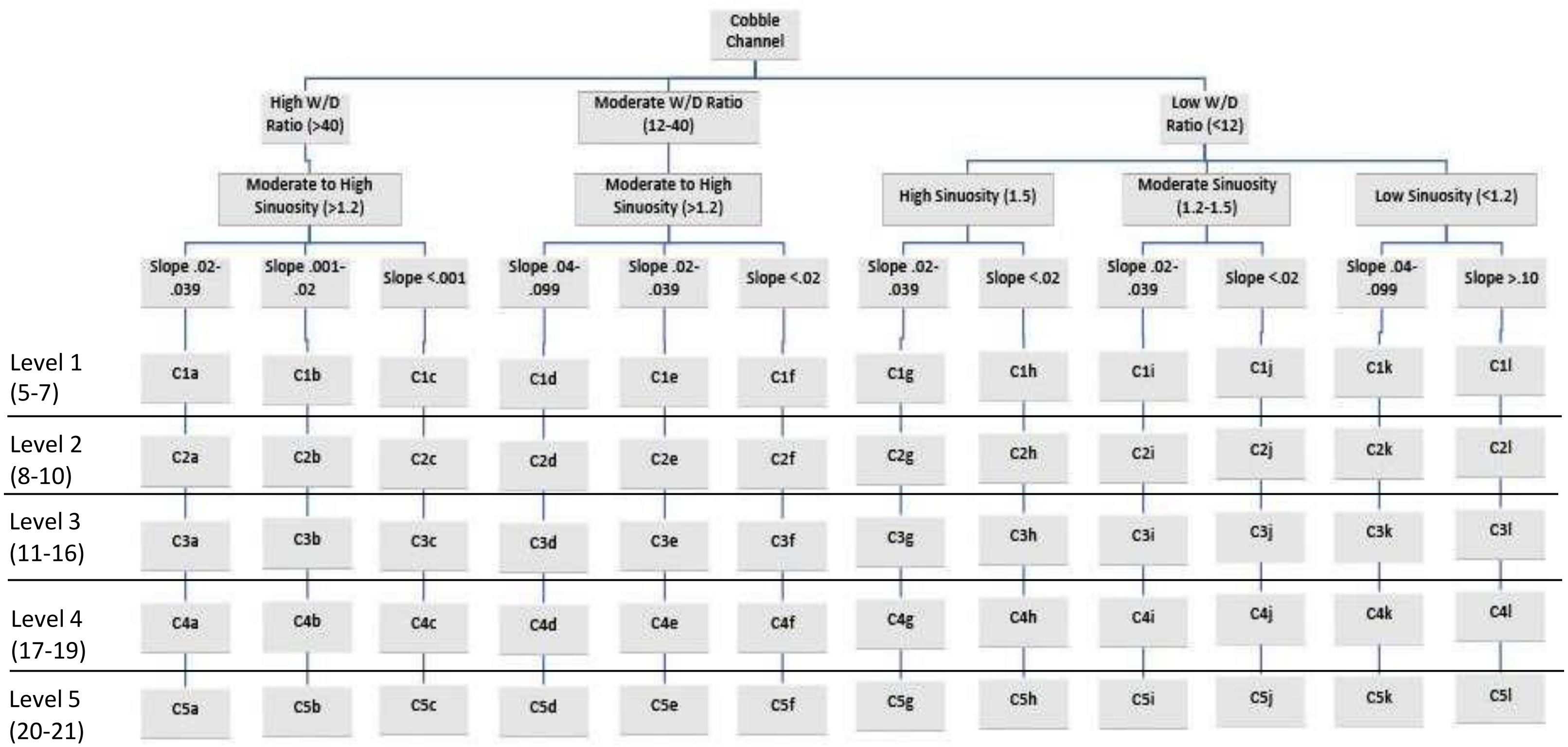

Figure 65: Detailed classification key for cobble (Type C) channels.

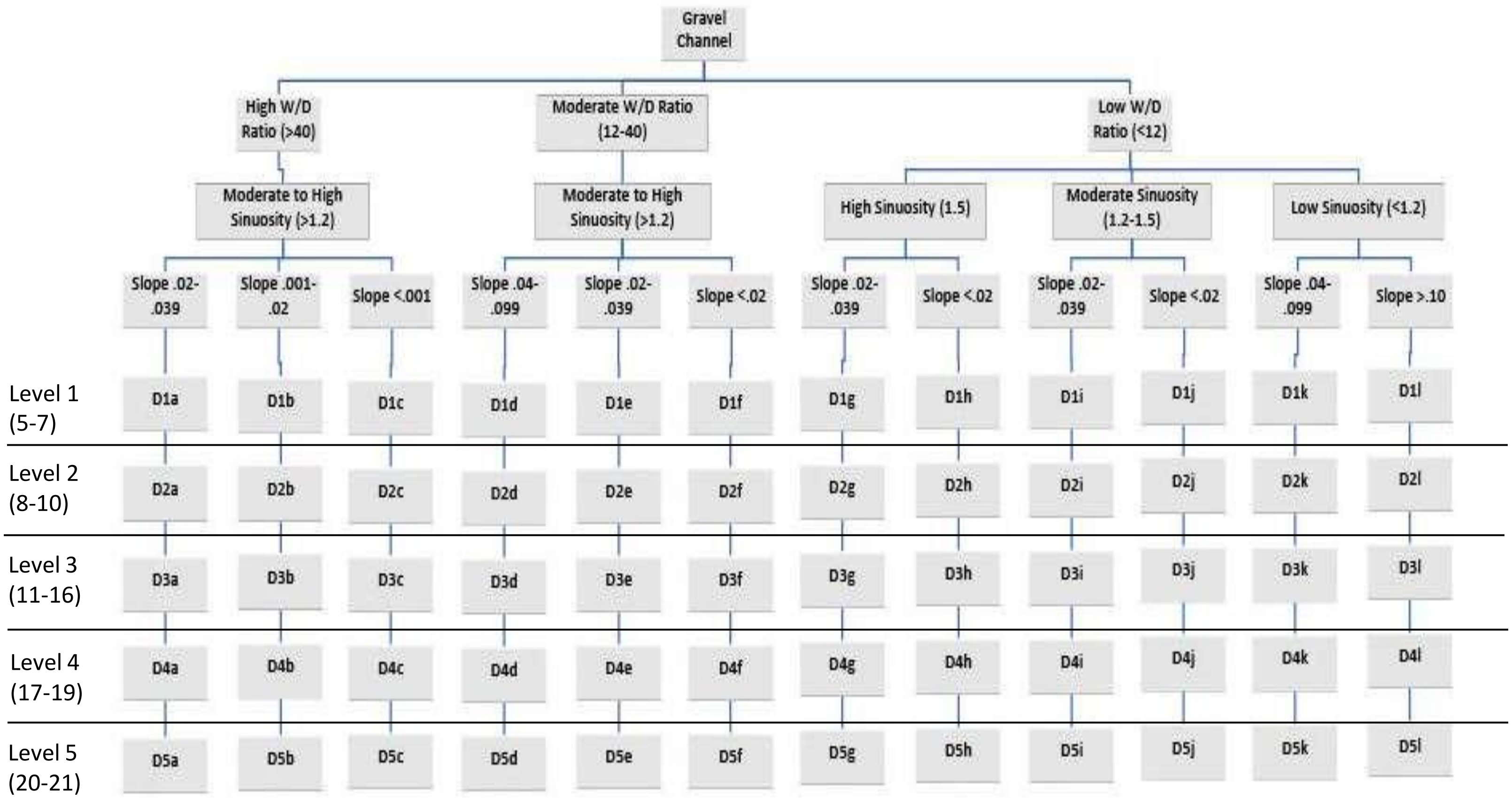

Figure 66: Detailed classification key for gravel (Type C) channels

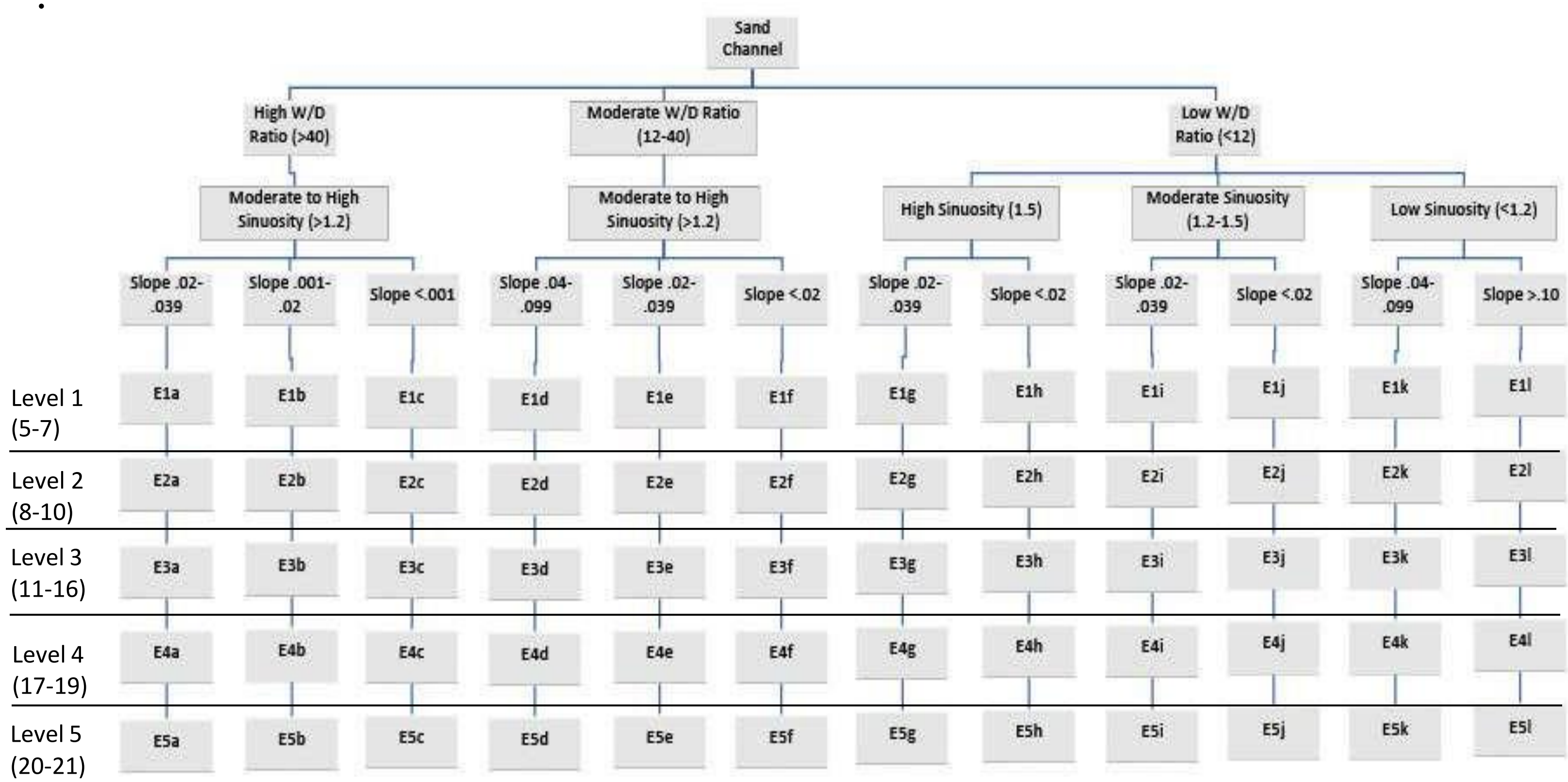

Figure 67: Detailed classification key for sand (Type E) channels

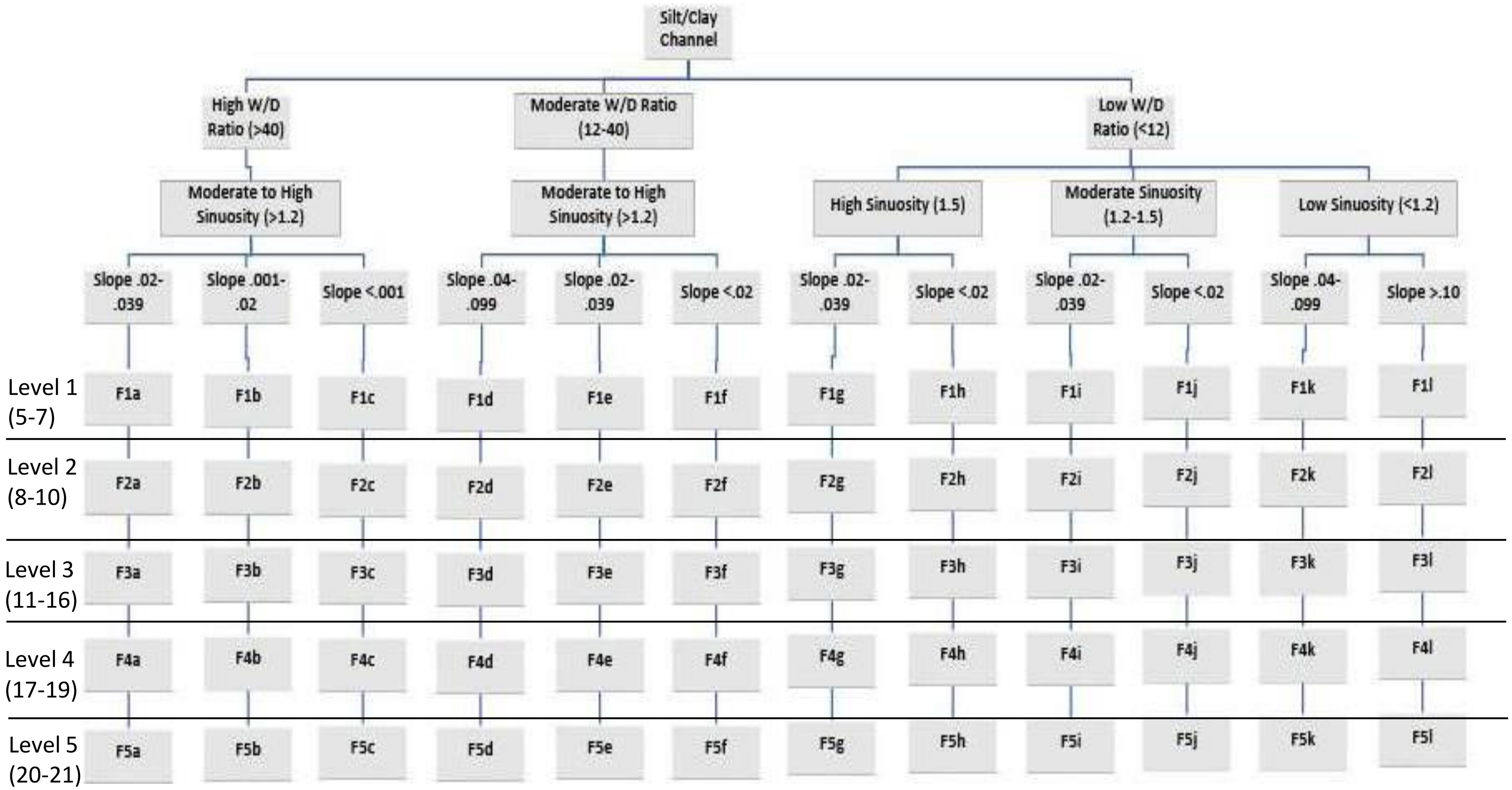

Figure 68: Detailed classification key for silt/clay (Type F) channels.

4.4 Conclusion

The plethora of river classification schemes already produced offers a choice of assessment and implementation options for any practitioner. It is hardly a novel undertaking to propose a classification scheme, but the one proposed here attempts to fill specific gaps in previous schemes: the difficulty of assigning bankfull stage in Coastal Plains Rivers and the modern impact of anthropogenic modification to river channels and/or watersheds. Bankfull stage and processes for its determination have been defined by multiple researchers over the years, and still no precise method of its determination has been established for low-gradient Coastal Plains rivers. Thus, the concept of bankfull zone is proposed as an alternative. In most favorable channel conditions, bankfull zone will narrow to the same bankfull stage which would be agreed upon by traditionalists, but in more complex river channels the concept of bankfull zone allows a margin of error for determination of bankfull conditions. Future research should implement this classification scheme on different types of river channels within the Coastal Plains to assess its suitability.

4.5 References

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CHAPTER VI

ASSESSMENT OF STABILITY OF CHANNELS BASED ON MORPHOLOGICAL INDICATORS

6.1 Introduction

The population of the U.S. state of Texas grew 15 times faster than the national average during the years 1997-2012, with most growth occurring in urban settings. Much growth centered around the Dallas-Fort Worth Metroplex (DFWM) and in the Austin area, cities built on the banks of the Trinity River and the Colorado River, respectively. The spread of urbanization in watersheds and on the banks of major rivers poses a threat of accelerated morphological adjustment as the channel responds to hydrological changes in the watershed. Understanding the response of a river to such land changes is crucial to predicting response to continued urban spread and potential restoration requirements. Although investigations of the effects of urbanization on rivers are numerous, few have been conducted in the Gulf Coast region of the United States. Given the current population growth and projections for the region, it is necessary to understand effects of urbanization on the major rivers in the Gulf Coast and prepare for fluvial adjustments induced by the rapid expansion of its urban centers. This study assesses the morphological channel stability of the Brazos River near Waco, Texas, the Colorado River near Austin, Texas, and the Trinity River near Dallas, Texas, using qualitative morphological indicators. Results are compared with quantitative assessments of stream power, unit stream power, and changes in sediment size to ascertain the reliability of qualitative stability of a stream assessment of rivers in the Texas Gulf Coast plains.

River channels, by the very nature, are dynamic entities prone to regular adjustment (Schumm, 1972; Rosgen, 1994; Thorne, 1996b). The problem which arises from excessive adjustment is primarily a threat to human interests, not the longevity of the river (Thorne, 1996b). A primary challenge in assessing morphological stability of a river channel, then, is defining what is a "stable" and an "unstable" channel. Brice (1982) considers an unstable channel one whose rate or magnitude of change is great enough to be a significant factor in the planning or maintenance of a bridge, highway, or other structure. Thorne et al. (1996b) describes an unstable channel as actively changing its form through time and space and likely to show evidence of serious sustained aggradation, degradation, width adjustment or planform change. Stable streams are subsequently specified as dynamic or moribund, based on whether the channel adjusts in response to natural environmental fluctuations or only to imposed engineering efforts. Whereas dynamic stable streams generally have alluvial channels formed by the river itself, moribund channels often have channels which result from processes and conditions which happened in the past. These channels often exhibit low stream power, low gradients, and erosion-resistant banks. Lagasse et al. (2012) identify stream instability by the presence of lateral bank erosion, aggradation or degradation of streambed progressing with time, and/or short-term fluctuations in the elevation of the streambed usually associated with scour and fill. In this study, I consider a stable stream one which maintains its form or adjusts its channel at a rate consistent with rivers of the same form in similar climates and bedrock.

Many assessments of river stability were developed to assess the structural integrity of engineering structures which cross river channels (Pfankuch, 1978; Brice, 1982; Brooks, 1987; Thorne et al., 1996 a and b; Johnson et al., 1999; Doyle et al., 2000; Lagasse et al., 2012). In the Pfankuch (1978) method, channels are evaluated at the upper banks, lower banks, and bottom. At the upper banks mass wasting, debris jam potential, and vegetative bank protection are evaluated with rankings of excellent, good, fair, or poor. At the lower banks channel capacity, bank rock content, obstructions and flow deflectors, cutting and deposition are evaluated the same way. At the channel bottom, the same evaluation is used for rock angularity, brightness, consolidation and packing, the distribution of bottom sediment size and percent stable materials, scouring and deposition, and clinging aquatic vegetation. In this assessment, higher scores indicate lower stability and each ranking is pre-assigned a point value. This differs from Johnson, Thorne, and Booth in which the final score is a weighted average. Later assessment of the Pkankuch (1978) method found it lacking scientific basis or measurement precision to accurately predict extent or type of channel change (Morét, 1997). Brice (1982) developed a method for the Federal Highway Administration to assess stability of a stream based on type. In his method, type of stream is based on variability of width and presence of bars. He defines stream instability as lateral bank erosion, progressive degradation of the streambed, or natural scour and fill of the streambed. Brooks (1987) studied 46 river channels in England and Wales downstream of channelization works. His study considered stream power, channel cross-sectional width, shear bed and bank strength, and sediment size in their investigation of channel stability and compared location of modern channels to former ones using historical aerial photography and maps. Additionally, empirical measurements were taken over a three-year period using pins inserted into riverbanks. In his summary, measurements are combined to show changes in capacity, width and depth of channels with distance from engineering structures as well as threshold capacities downstream of channel construction. Historical data revealed occurrences of floods which exceeded the modified threshold which likely triggered erosion. In their reconnaissance of channel stability near engineering structures, Thorne et al. (1996b) considers the size of bed material (coarser sediment indicates higher stability), bed protection, stage of channel evolution, percentage of channel constriction, number of piers on channel, percentage of blockage, bank erosion on each bank, meander impact point from bridge in meters, pier skew for each pier, mass wasting at pier, high-flow angle of approach, and percentage of woody vegetation cover. The Federal Highway Administration (2006) developed a detailed method of assessing channel stability in different physiographic regions of the United States, but only two of the reference streams used were in the Gulf Coastal Plain: Alligator Creek and Peace River, both in Florida. Other stability assessments have been developed based on streams in Colorado (Rosgen, 2001) and Georgia (Mukundan, 2011). The method utilized in this study is presented by Doyle et al. (2000) and is a modification of the method by Johnson et al. (1999). Johnson et al. (1999) present a weighted average of 13 stability indicators, each ranked excellent, good, fair, or poor. Each stability indicator was given a pre-assigned weight based on its influence on channel morphology and ranked excellent (1-3), good (4-6), fair (7-9), or poor (10-12). This procedure was developed to determine stability of gravel-bed rivers at road crossings and culverts to avert bridge failure resulting from channel adjustment and was implemented on streams in Pennsylvania and Maryland, then modified by Doyle et al. (2000) for application to gravel streams in Indiana.

6.2 Study Area

The Brazos, Colorado, and Trinity Rivers in Texas were assessed for channel stability upstream and downstream of respective urban centers (Figure 70).

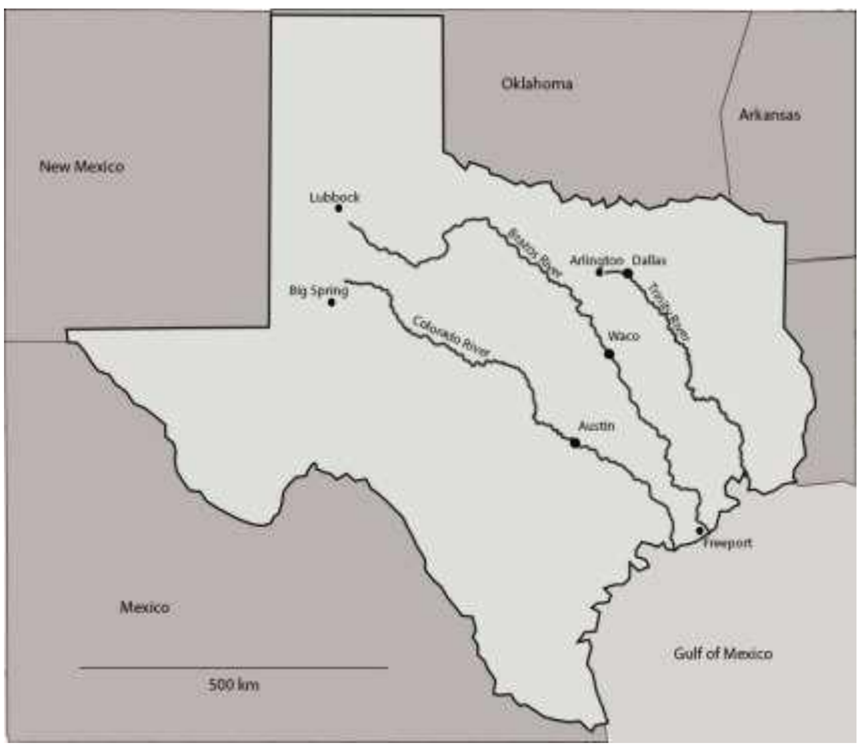

Figure 70: Rivers assessed for morphological stability in this study. Each river was assessed upstream and downstream of Dallas, Waco, and Austin, respectively.

6.2.1 Brazos River at Waco, Texas

The Brazos River extends 1,352 km from the confluence of its Salt Fork and Double Mountain Fork in Stonewall County to its mouth in the Gulf of Mexico near Freeport in Brazoria County (Hendrickson, 2019). The longest river in Texas, the Brazos River has the highest average annual discharge of any Texas river at 7.4 km^3/s (Texas State Historical Association, 2018; Hendrickson, 2019). This study examines a ~27 km reach beginning ~12 km upstream of the city of Waco and extending ~11 km downstream of Waco (Figure 70). Waco has an estimated population of 268,696 as of 2017 (United States Census Bureau, 2018), and the Brazos River flows directly through the city. Near Waco, the Brazos River flows through Cretaceous-aged Austin Chalk, the Wolfe-City Formation, and the Ozan formation. These units exhibit interbedded limestone, marl, sandstone, and clay. The Brazos River was assessed for morphological stability on July 5 and 6 of 2019. Gage height on these dates ranged from 3.0-6.0 ft (.9-1.8 m) and discharge ranged from 1,000 to ~4,000 ft^3/s (28-113 m^3/s). The river was not observed during bankfull flows for safety consideration, and as an attempt to observe the river at flows which approximate average. Waco received 7.38 inches (18.75 cm) of precipitation during the month of June 2019.

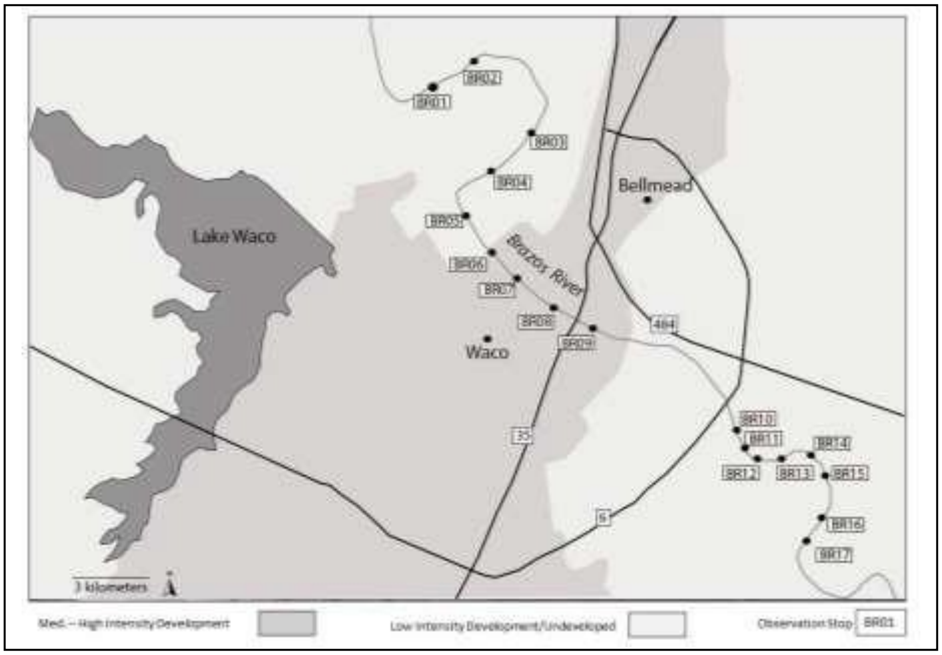

Figure 71: Observation locations on the Brazos River near Waco, Texas

This reach of the Brazos River flows through a modified stretch in Waco where the channel has been often reinforced with stone or wood and vegetation cleared (Figure 72).

Figure 72: Modified channel on the Brazos River in Waco, Texas.

Upstream of Waco, the river flows through natural alluvium or limestone bedrock channels (Figure 73).

Figure 73: Limestone and alluvium channels upstream of Waco, Texas.

Immediately downstream of the most urbanized reach, a labyrinth weir manages water levels for flood control and creates the colloquially called Lake Brazos (Figure 74). This weir should not be confused with the nearby Lake Waco Dam, which crosses the Bosque River.

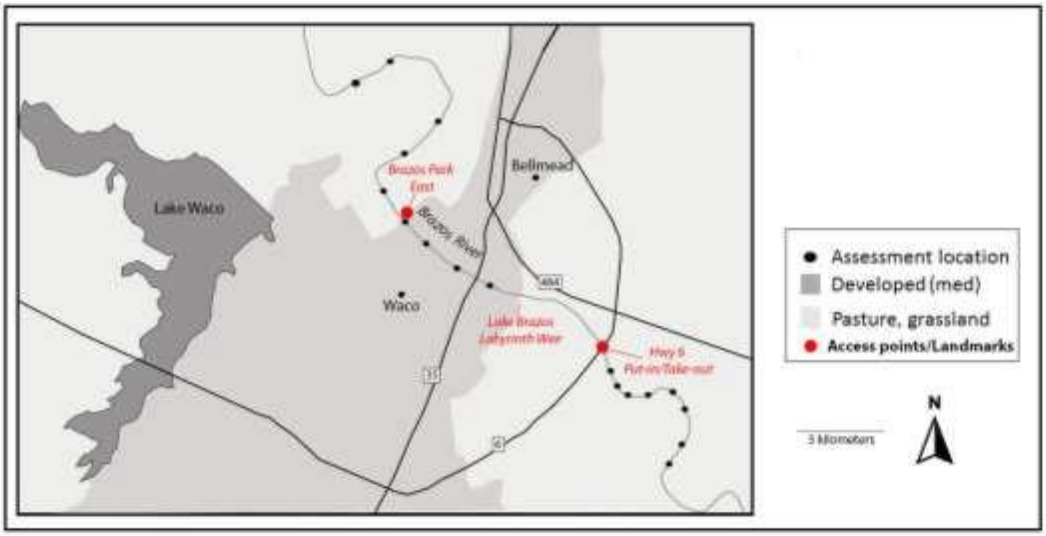

Figure 74: Access points and landmarks on the Brazos River near Waco, Texas.

The Brazos River Authority does not release water from dams in anticipation of excess precipitation, but in response to upstream and in-city gage readings (Brazos River Authority, 2019). Upstream put-in and take-out was at Brazos Park East. River flow levels allowed paddling downstream and upstream with considerable effort thus no separate take-out was used. Downstream of Waco, put-in and take-out was near the Hwy-6 overpass, where flow levels again allowed for returning by paddling upstream with effort. Landcover downstream of Waco returns to undeveloped or low-intensity development, with a mostly natural channel (Figure 75).

Figure 75: Natural vegetation on banks of Brazos River downstream of Waco, Texas.

6.2.2 Colorado River at Austin, Texas

The Colorado River extends 1,387 km from its headwaters near Lubbock, Texas, to the Gulf of Mexico and has a total drainage area of 103,341 km2 (Kammerer, 1987). This study assesses the river in the vicinity of Austin, Texas. Austin has a population of 950,715 as of 2017 (United States Census Bureau). The Colorado River in the observed reaches cuts through the Cretaceous-aged Upper Glen Rose Limestone (limestone, dolomite, and marl), the Fredericksburg Group (limestone, dolomite, and chert), and Austin Chalk. Channel slope in the study reaches is ~.0006. Average annual discharge of the Colorado River is 2.34 km^3/s (Texas State Historical Association, 2018). Urban sprawl associated with Austin extends significantly to the northwest, following the Colorado River upstream. For this reason, observations of the river in a natural state upstream of Austin urbanization and suburbanization had to occur near Smithwick, Texas, approximately 50 miles (80.5 km) northwest of Austin (Figure 76). Despite the distance, the Colorado River in

Smithwick flows through the same geology and climate as in Austin, and thus allows for comparison of channel morphology before the effects of urbanization.

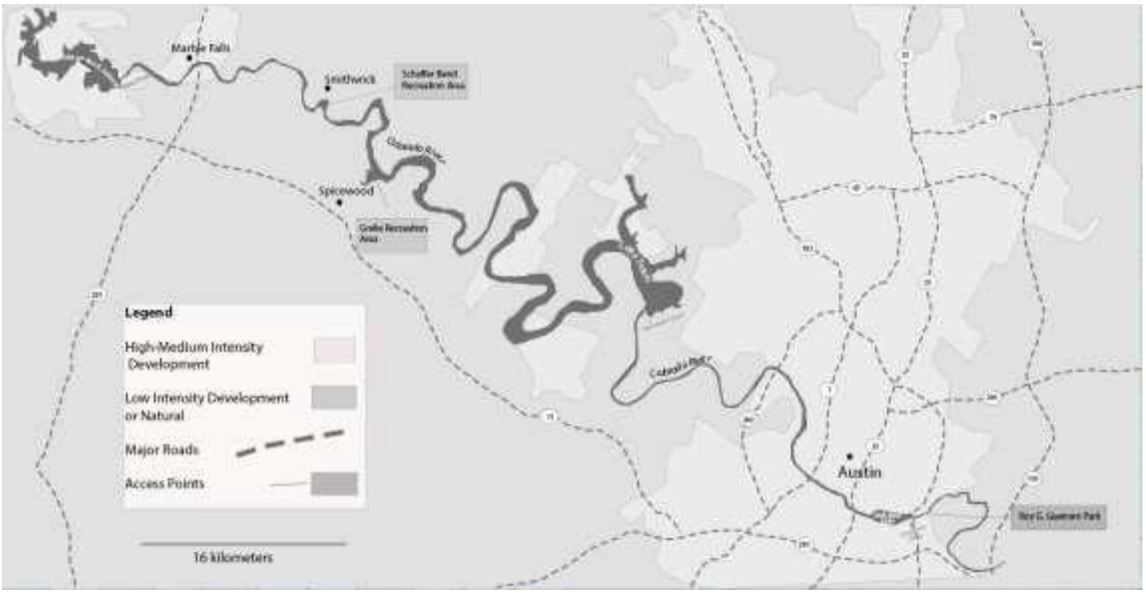

Figure 76: Location of study reaches and access points on the Colorado River near Austin, Texas.

Put-in for the upstream reach was at the Shaffer Bend Recreational Area, managed by the Lower Colorado River Authority (LCRA) and take-out was at the Grelle Recreational Area, also managed by the LCRA (Figure 77).

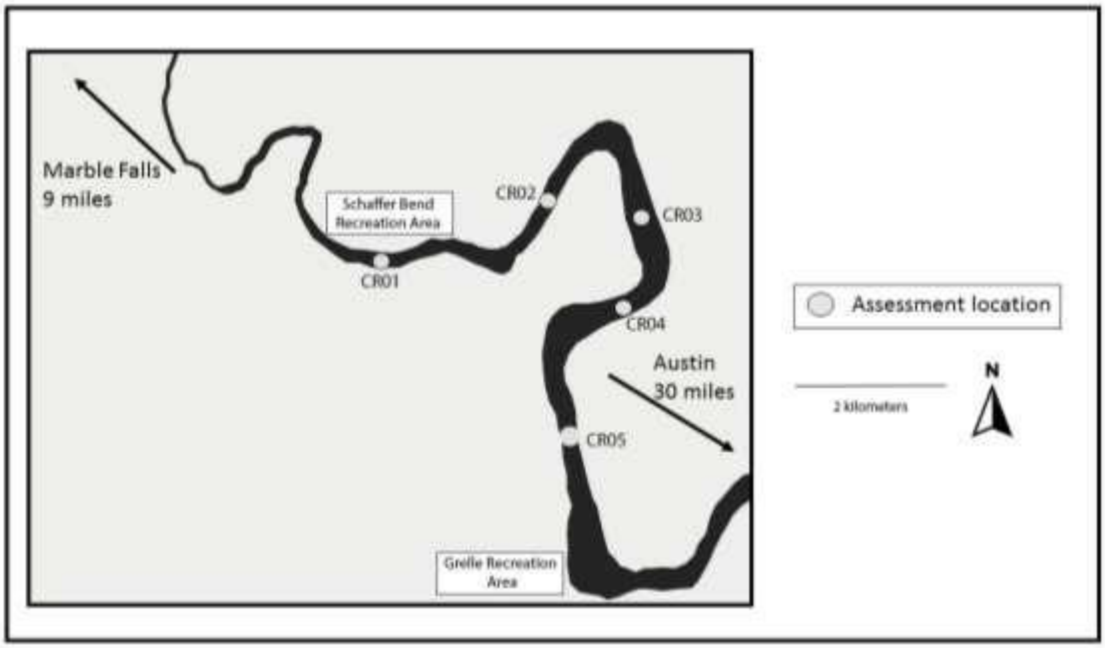

Figure 77: Access points and observation points in the upper portion of the Colorado River.

In the upstream reaches, landcover along the river channel is mostly shrub/scrub and forest, with no development or low-intensity development (Figure 78).

Figure 78: Colorado River channel in the vicinity of Spicewood, Texas, upstream of Austin, Texas.

The Colorado River was assessed during June 6-8, and June 14-15, 2019. Discharge ranged from 4,000 to ~4,500 ft^3/s (113-127 m^3/s) during June 6-8 and 1,500-3,000 ft^3/s (42.5-85 m^3/s) during June 14-15. Gage height on June 6-8 averaged 16.17-16.75 ft. (~5 m) and on June 14-15 averaged 12.5-15.5 ft (3.8-4.7 m). Austin received 7.52 inches (19.1 cm) of rain in May 2019.

Two dams affect the Colorado River near Austin. Mansfield Dam creates Lake Travis, about 30 km upstream of Austin, and Longhorn Dam creates Lady Bird Lake in the Austin city limits. The river flows for approximately 43 km between the two dams, through heavily suburbanized and urbanized channel reaches. The suburban reaches have been continuously stabilized using wood or stone, and flow through alluvium or limestone bedrock channels. Interestingly, much of the urban reaches exhibit less stabilization, though wood and concrete stabilization does exist in some areas (Figures 79, 80). Access to the river in Austin is readily available at the I-35 overpass or farther upstream at Rowing Dock, a canoe and paddle board rental business. Flow is slow enough that paddling both downstream and upstream is possible, thus no separate take-out location is necessary.

Figure 79: Heavily urbanized bank in Austin, Texas. Notice only moderate bank stabilization.

Figure 80: Other reaches within Austin had no channel stabilization features. A closeup of the bank in the top image is presented in the bottom image.

The Colorado River was accessed downstream of Austin at the Roy G. Guerrero Park near Longhorn Dam (Figure 81).

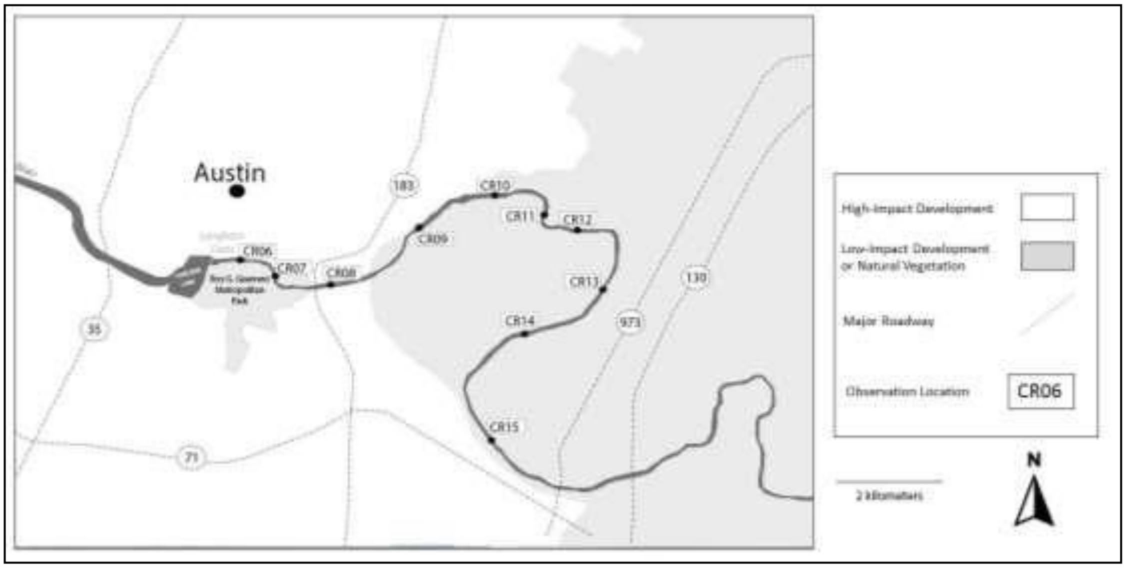

Figure 81: Observation locations on the Colorado River downstream of Austin, Texas.

Access here is a favorite for kayakers, though accessing the river with a canoe is a challenge. Take-out was the FM-973 overpass. Downstream of Austin, the Colorado River flows through a natural channel with undeveloped banks (Figure 82).

Figure 82: Colorado River channel immediately downstream of Austin, Texas.

Landcover is pasture, shrub/scrub, or low-medium intensity development. Two locations in the study area create flow disruptions: a weir precariously placed beneath the US-183 overpass such that it does not appear on aerial photographs and surprises unsuspecting canoeists, and a recreational standing wave at a southward bend of the channel 10 km downstream of Longhorn Dam (Figure 83). Future researchers are advised to consult aerial photographs before canoeing this reach, because the placement of the standing wave on a bend causes it to be out of sight until one is directly upon it.

Figure 83: Artificial standing wave on the Colorado River downstream of Austin, Texas. The location of the wave on a sharp bend causes it to be out of sight until one is directly upon it.

6.2.3 Trinity River at Dallas, Texas

The Trinity River originates at the confluence of West and Elm Forks northwest of Dallas, Texas and east of Arlington, Texas. It extends 1,142 km to its mouth at Trinity Bay in Chambers County, Texas (Figure 84). Average annual discharge is 7.03 km^3/s. In this study area, the Trinity River originates in Cretaceous-aged limestone, shale and sandstone of the Eagle Ford Group before flowing southwest through the Austin Chalk, lower Taylor marl, and calcareous silt and sand of the Neylandville and Marlbrook Marl formations, both Taylor group.

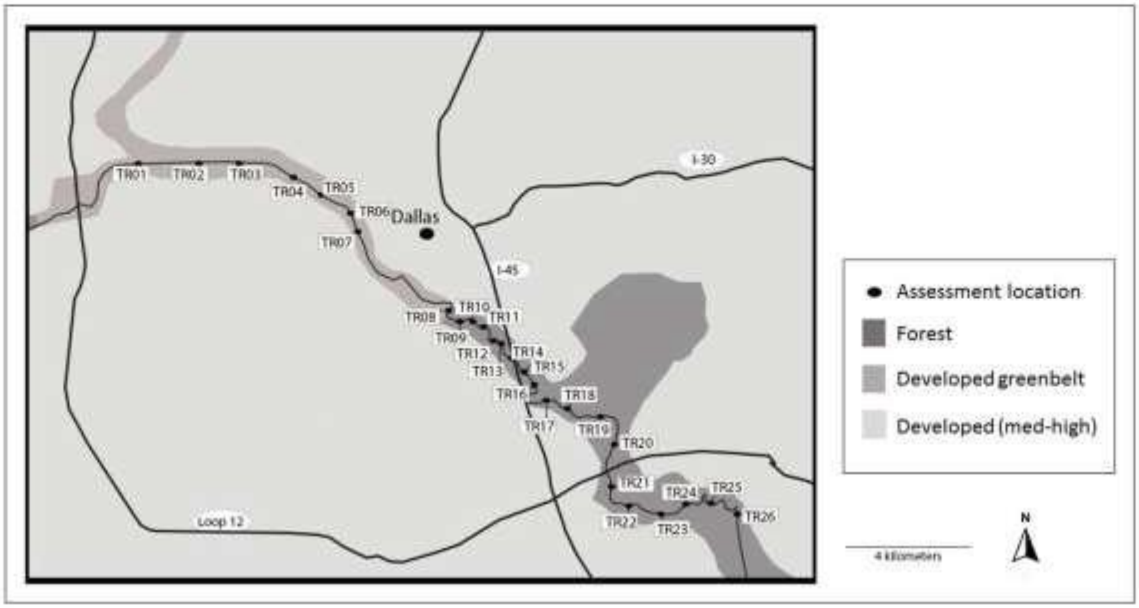

Figure 84: Access and observation points on the Trinity River near Dallas, Texas.

Assessment begins at the confluence of the West Fork and Elm Fork, marking the origin of the Trinity River main channel. Although this reach is geographically within an urbanized region of the Dallas-Fort Worth-Arlington metroplex, the channel is unaltered by engineering structures and retains a wide greenbelt on either bank extending nearly half a kilometer on each side of the river (Figure 85).

Figure 85: Trinity River upstream of Dallas, Texas

As the river turns southwest through the city of Dallas, the greenbelt ceases to exist, and the channel is reinforced with concrete. In the southeastern portion of the city, channelization ends as the river flows into the protected Great Trinity Forest and continues as a natural channel (Figure 86). No dams are present on this stretch of the Trinity, although a constructed standing wave was emplaced at the Santa Fe railroad trestle. Though present for the first field excursion in May of 2018, this was removed during June-November 2018.

Figure 86: Trinity River channel within and downstream of Dallas, Texas.

The Trinity River was assessed in 2018 on May 17, June 10, and July 27. Gage height on May 17 averaged 15.5 ft. (4.7 m), on June 10 averaged 15.4 ft. (4.7 m), and on July 27 averaged 12.6 ft. (3.8 m). Discharge during Excursion 1 averaged 474 ft^3/s (13.4 m^3/s); during Excursion 2 averaged 402 ft^3/s (11.4 m^3/s); and during Excursion 3 averaged 233 ft^3/s (6.6 m^3/s). Bankfull discharge was avoided for safety considerations, and to take measurements which approximated the average flow of the river. Dallas received 1.87 inches (4.5 cm) of rain in May 2018, 1.27 inches (3.2 cm) in June 2018, and 0.25 inches (.64 cm) in July 2018.

6.3 Methods

6.3.1 The Brazos River near Waco, Texas

A six-mile stretch of the Brazos River was studied, beginning Brazos Park East and ending approximately six miles upstream (Figure 70). Nine sites were sampled along this segment, to discern the stability of the Brazos River upstream of the urbanization of Waco, Texas. At each site, a localized assessment of channel stability was made based upon the Modified Johnson et al. (1999) Method for Assessing Channel Stability, developed and used by Doyle et al. (2000).

To assess channel stability within an urbanized reach, a 3.5-mile stretch of the Brazos River as it passes through Waco, Texas, was studied. This reach begins at Brazos Park East upstream of Waco and ends at Lake Brazos, formed by the labyrinth weir downstream of the city (Figure 70). Six locations were studied on this reach. Downstream of Waco, a 4.25-mile stretch of the Brazos River was studied beginning at the Hwy 6 overpass and continuing to the end of a wide meander approximately 4.25 miles downstream. Ten locations were assessed on this reach.

6.3.2 The Colorado River near Austin, Texas

The Colorado River was studied upstream of Austin, Texas near Spicewood, Texas. Put-in was at Shaffer Bend Recreation Area, 55 miles northwest of Austin and managed by the Lower Colorado River Authority (LCRA). Take-out was 5.6 miles downstream at Grelle Recreation Area, also managed by the LCRA (Figure 75). In this region, the river flows through a slightly modified or natural channel. Prior urbanization exposure is slight, as at this point the Colorado River has flowed through no cities larger than Marble Falls, Texas (population 6,514). The reach between Shaffer Bend and Grelle Recreation Areas were selected because suburbanization and urban sprawl related to Austin extends beyond Lago Vista then decreases towards Grelle Recreation Area. This was an opportune reach to observe the Colorado River without the effects of urbanization from Austin but with similar geology and climate. The Colorado River downstream of Austin was studied from Longhorn Dam to FM 973, approximately 11 miles downstream (Figure 80). River velocity is generally high here, resulting from water release from Longhorn Dam. At each site, a localized assessment of channel stability was made based upon the Modified Johnson et al. (1999) Method for Assessing Channel Stability, developed and used by Doyle et al. (2000).

6.3.3 The Trinity River near Dallas, Texas.

Assessment of the Trinity River near Dallas, Texas began at the confluence of

Mountain Fork and West Fork between Irving and Dallas. Although this region is within an urbanized area, wide greenbelts (~420 meters on either side of channel) are maintained throughout. Assessment continued into Dallas downstream, beyond the boundary between urbanization and the Great Trinity Forest (Figure 83). To assess the status of the Trinity River downstream of urbanization, a 10-mile reach was studied, through the Great Trinity Forest downstream of the Loop 12 overpass. The Great Trinity Forest is a 6,000-acre bottomland forest which borders the Trinity River for approximately 11 miles. At 15 locations along this reach, a localized assessment of channel stability was made based upon the Modified Johnson et al. (1999) Method for Assessing Channel Stability, developed and used by Doyle et al. (2013).

6.4 Results

Detailed synopses of scores for stability for each stop on each river are presented in Appendix B. A summary of stability scores is presented in Table 17. Stability and score are inversely related.

Trinity River Stability Score	
Upstream Average	27.49
Downstream Average	31.51

Brazos River Stability Score	
Upstream Average	21.93
Downstream Average	25.16

Colorado River Stability Score	
Upstream Average	20.4
Downstream Average	26.44

Table 17: Average stability scores for each study river. Higher scores indicated reduced stability.

6.4.1 Brazos River near Waco, Texas

Average scores for stability for the Brazos River near Waco, Texas, are presented in Table 18. Scores for stability for all stops on the Brazos River are presented in Figure 90.

Upstability of a stream Average	**21.93**
Highest Stability Score (Upstream)	26.6
Lowest Stability Score (Upstream)	16.4
In City Stability Average	**24.28**
Highest Stability Score (City)	31
Lowest Stability Score (City)	16.6

Downstream stability Average	**26.04**
Highest Stability Score (Downstream)	28.8
Lowest Stability Score (Downstream)	21.4

Table 18. Summary of Stability Scores for the Brazos River near Waco, Texas. Higher scores indicate lower stability.

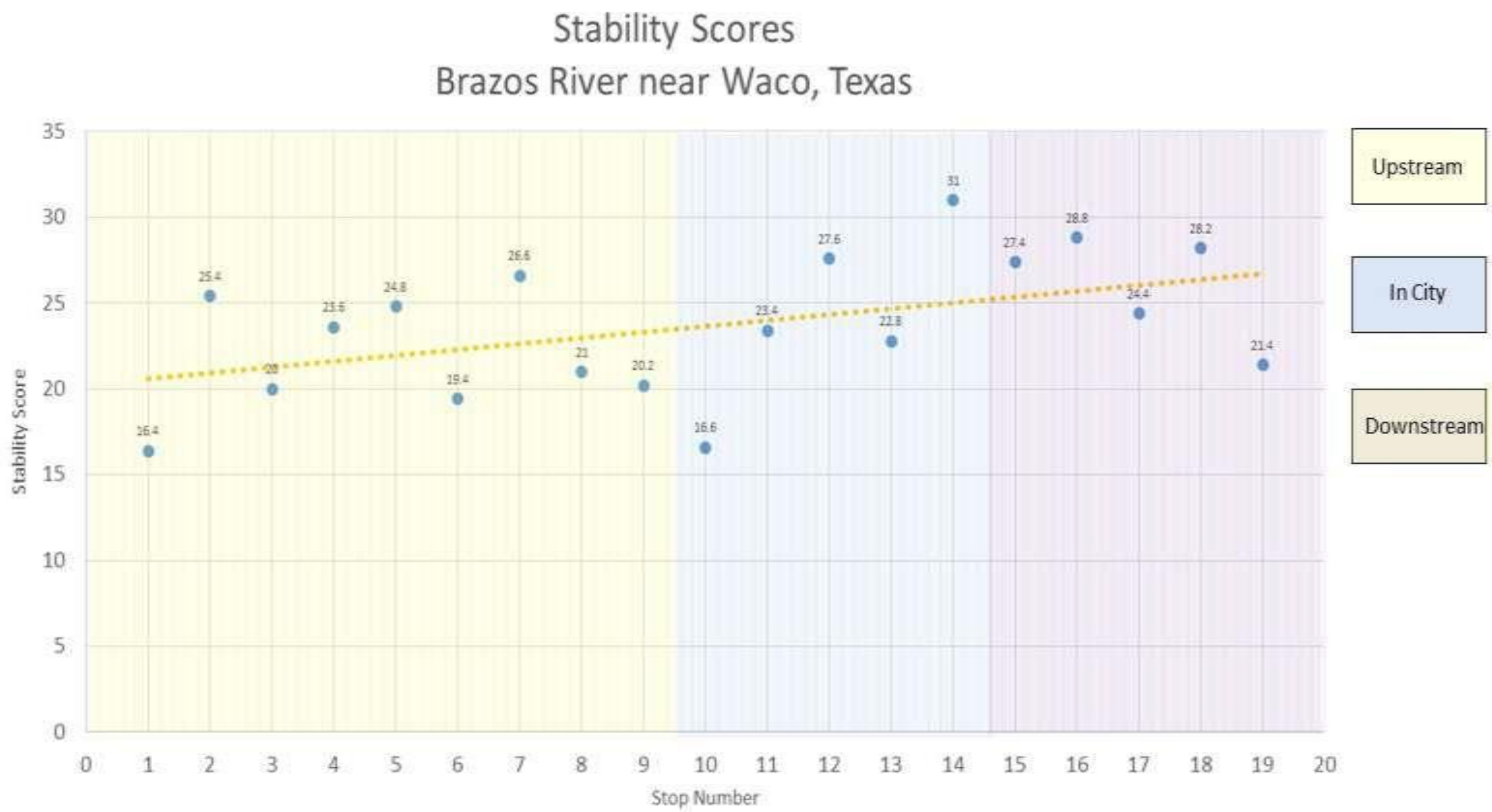

Figure 87: Stability scores on the Brazos River near Waco, Texas.

6.4.2 Colorado River near Austin, Texas

Average stability scores for the Colorado River near Austin, Texas, are presented in Table 19. Stability scores for all stops on the Colorado River are presented in Figure 91.

Upstability of a stream Average	**20.4**
Highest Stability Score (Upstream)	31.6
Lowest Stability Score (Upstream)	10.6
In City Stability Average	**29.9**
Highest Stability Score (City)	33.8
Lowest Stability Score (City)	26
Downstability of a stream Average	**25.58**
Highest Stability Score (Downstream)	33.4
Lowest Stability Score (Downstream)	21.4

Table 19: Stability scores for the Colorado River near Austin, Texas.

Figure 88: Stability scores on the Colorado River near Austin, Texas.

6.4.3 Trinity River near Dallas, Texas

Average stability scores for the Trinity River near Dallas, Texas, are presented in Table 10. Stability scores for all stops on the Trinity River are presented in Figure 92.

Table 20: Average stability scores for each study river. Higher scores indicate reduced stability.

Upstability of a stream Average	**28.6**
Highest Stability Score (Upstream)	31.6
Lowest Stability Score (Upstream)	23.8
In City Stability Average	**27.2**
Highest Stability Score (City)	32.2
Lowest Stability Score (City)	23.2
Downstability of a stream Average	**31.47**
Highest Stability Score (Downstream)	37.4
Lowest Stability Score (Downstream)	24.2

Figure 89: Stability Scores for Trinity River near Dallas, Texas

6.5 Discussion

6.5.1 Challenges and Opportunities Presented by Each River

The three rivers in this study posed unique challenges and opportunities regarding accessibility, location of the respective urban setting, and variability of LULC in the watershed. Those challenges are represented in the variability of observation points upstream, in city, and downstream, in each river.

The Trinity River originates at the confluence of West Fork and Elm Fork, approximately six miles west of the Dallas city center. In this region the channel is already in an urbanized watershed, because urbanization of the cities of Irving and Grand Prairie extend to and blur with the city of Dallas. The channel in the region of West Fork and Elm Fork, however, is protected by Mountain Creek Preserve, managed by the city of Irving, and extensive, wide greenbelts. Near the city center, the greenbelts narrow and change to highly maintained areas with reduced native riparian vegetation and a reinforced channel. Just south of the Dallas city center, the Great Trinity Forest creates an immediate and abrupt transition to natural LULC and river channel. The largest urban forest in the United States, the Great Trinity Forest extends over 6,000 acres and is part of the larger Trinity River Project, slated to be one of the largest urban parks in the world at 10,000 acres. The extent of the Great Trinity Forest coupled with the significant modification of the river channel in Dallas allows an opportunity to observe recovery of a river channel after intense alteration. Stability of the Trinity River downstream of Dallas was notably lower than upstream. Most obvious changes were observed in the vegetation (exposed roots, leaning trees) and bank stability (scalloped beds, mass wasting events). Compared to an average upstream score of stability of 27.7, stability score immediately downstream of the Dallas city center jumped to 37.4 (Higher numbers indicate lower stability). As the river continues through the Great Trinity Forest, it regains stability with distance from human modification. This demonstrates the value of urban forests and nature preserves as entities to sustain morphological stability, in addition to the more commonly touted benefits of carbon sequestration and ecological health.

The Brazos River near Waco, Texas, offered the best layout for equivalent numbers of observation points upstream of the city, in the city, and downstream of the city. Observation began approximately six miles upstream of Waco, where the channel flows through grassland and pasture with modification in the form of floating docks and boat access ramps only. Development of Waco begins abruptly, with little sprawl. Waco represents moderate intensity development with extensive developed open space in the form of sports fields and public parks. In Waco, the Brazos River is stabilized with permeable and impermeable structures and slowed by a large weir immediately downstream of Baylor University. Downstream of Waco, the river returns to an unmodified state and is flanked again by grassland and pasture, with some low intensity development. This case study offers an opportunity to compare the effects of different management styles. In the city, the river and watershed were more highly modified but the channel within the city and immediately downstream, beyond stabilization features, maintained stability. Farther downstream, local suburban development with little regulation extends to the channel with no stabilization features. The channel at these stops shows severely reduced stability as indicated by bank failure and rapid lateral migration.

The Colorado River near Austin, Texas presented a challenge because of the extent of urbanization and suburbanization of Austin to the northwest (upstream direction), making it difficult to locate observation points as examples of the river pre-urbanization. Initially, canoe put-in for the Colorado River was at the Emma Long Metropolitan Park, just upstream of Austin with the intention of traversing upstream beyond the effects of urban sprawl. Once on the ground, it became apparent that the channel remained highly altered even to Mansfield Dam, approximately 27 miles upstream of the Austin city center. Mansfield Dam creates Lake Travis, and the modification of the river intensifies again in its vicinity with the suburban sprawl of cities Hudson Bend, Lakeway, and Lago Vista. To fully escape the urban and suburban sprawl of the Austin area, upstream observations were made near Smithwick, Texas, 76 miles upstream of the Austin city center. Put-in was at the Shaffer Bend Recreation Area, and take-out was at the Grelle Recreation Area, both operated by the LCRA.

The Colorado River was striking, however, in its similarity of stability rankings upstream and downstream of such a large urban area. Of all three rivers observed, the Colorado exhibited the least degradation in channel morphology after urbanization. This is a testament to the role of water management and policy on the stability of a river channel.

6.5.2 Role of Management and Policy

Although many studies of the effects of urbanization on the morphological stability of rivers have focused on engineering structures and LULC alteration, I am aware of none that considers natural resource management in its assessment. This is a vital component of river stability which should not be overlooked. In some cases, natural resource management overlaps with LULC considerations (e.g. establishment of an urban forest in the watershed to counter the effects of intense upstream urbanization.) In other situations, this refers specifically to management of the river itself. It is not sufficient to note that a dam exists on a river during stability assessments. One must also consider how often releases occur, and for what purpose. In my opinion, this was the most significant factor determining downstream morphological stability for the three rivers.

The LCRA manages the Colorado River in Texas and its seven dams. By the time the river reaches Austin, it has passed through six of them. The dams on the Colorado River are all utilized for hydroelectric power. Hydroelectric dams use the power of moving water to turn turbines and generate electricity and can control the amount of water moving through the dam to generate the appropriate level of electricity when it is needed. Because electric demands are predictable on an hourly and daily cycle, it is reasonable that the hydroelectric dams have developed a cyclical schedule of water release to meet these demands. Given enough time, rivers will adjust to the cycle of regularly varied flow. In the case of Austin, Texas, a secondary effect of these regular releases is reasonably constant surface water levels, reducing the flashiness of flow predicted in other studies. Figure 93 compares the height of river gages of the three rivers in this study over a one-year period. Gage height varies within approximately 15 feet on the Colorado River and on the Brazos River, and 25 feet on the Trinity River. On both the Colorado and Brazos rivers, heights of the gage fluctuated within 2-5 feet on a regular basis, with high flow events in May-June which caused gage heights to increase 15 feet. In the Trinity River, seasonal gage heights were longer, with highest gage heights from January to July.

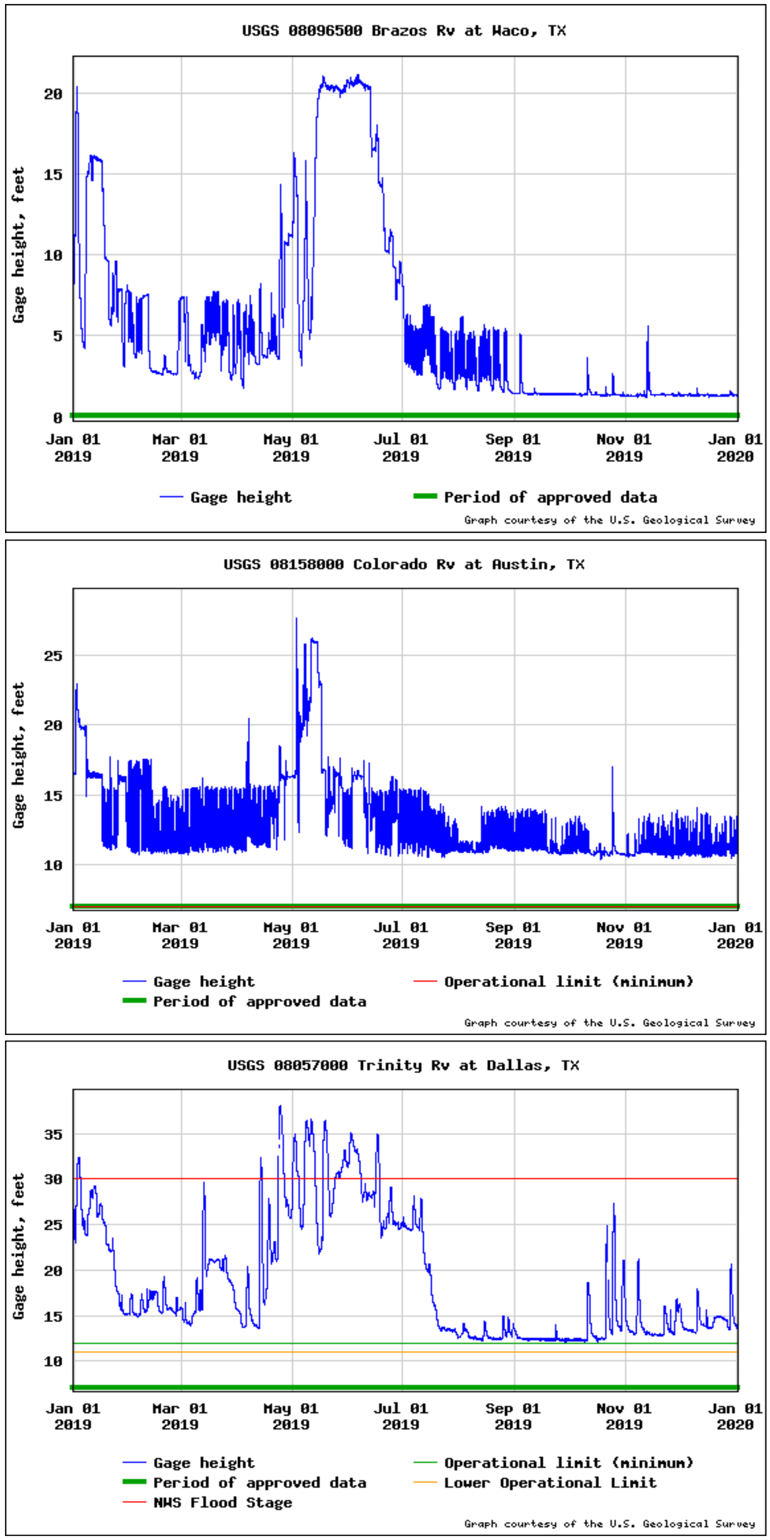

Figure 90: Annual gage heights on each of the three study rivers.

6.5.3 Correlation of Other Stability Indicators

This study was performed in conjunction with assessments of stream power, bed sediment size, and land cover upstream and downstream of urban centers. Findings supported previous studies which emphasize the uniqueness of each river and the inability of making general predictions of channel stability based on diagnostic properties alone, without consideration of local river management practices.

Average sediment size at each stop had a minor influence on the score of stability (Figures 94, 95). Percentage of development in the watershed had a minor effect on stability. In general, rivers were most stable in the urbanized reach as a result of artificial stabilization features. Watersheds downstream of stabilization regularly exhibited lower stability (indicated by a higher numerical score) (Figure 96).

At the Trinity River and Brazos River, values for stream power were closely correlated to stability scores. Downstream of urbanization at these two locations, stream power decreases but still increases and decreases in tandem with scores of stability, with some exceptions. At the Colorado River, stream power is likewise correlated to stability ratings and increases downstream of urbanization (Figure 97).

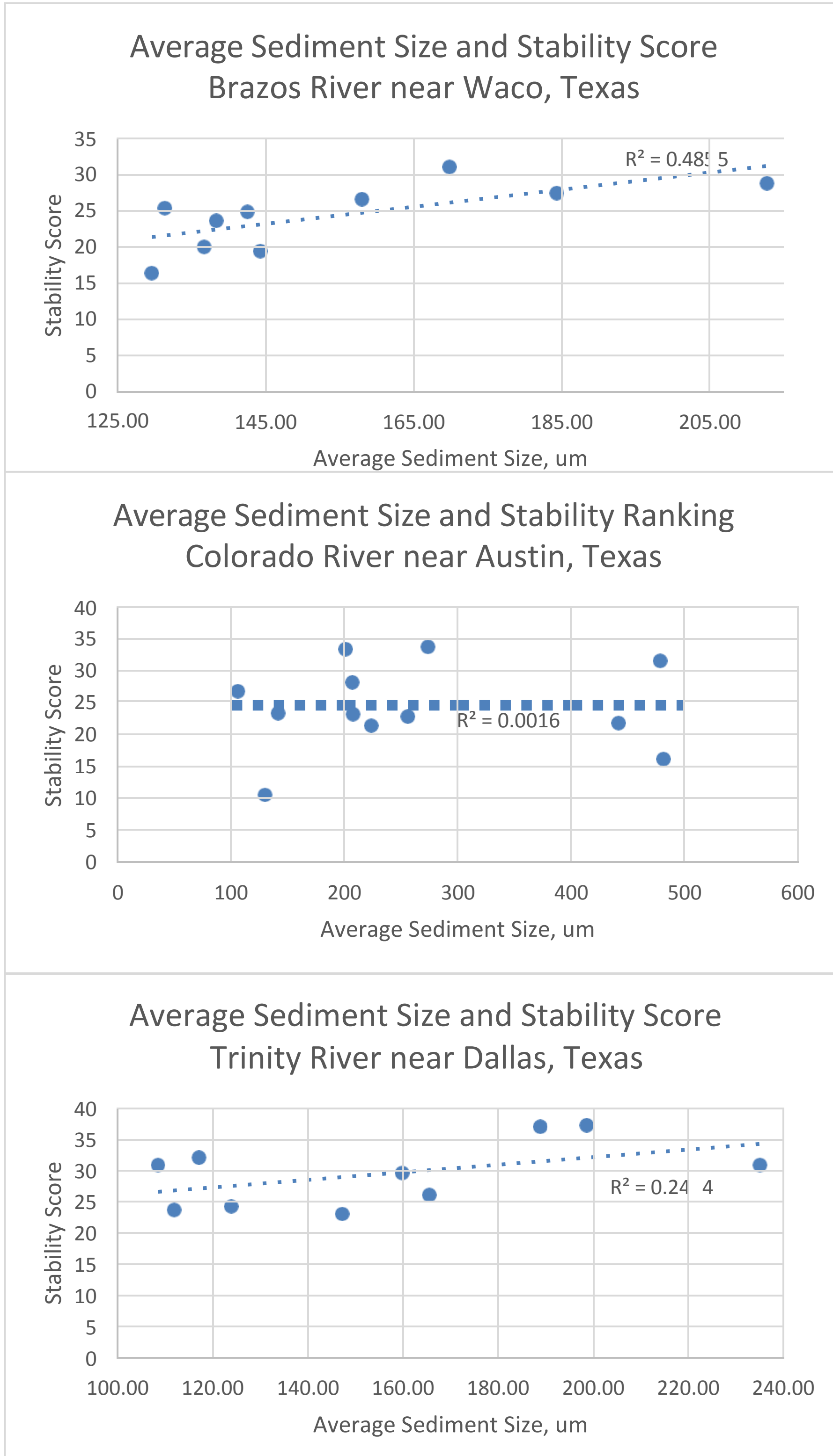

Figure 91: Average sediment size and stability scores at study rivers.

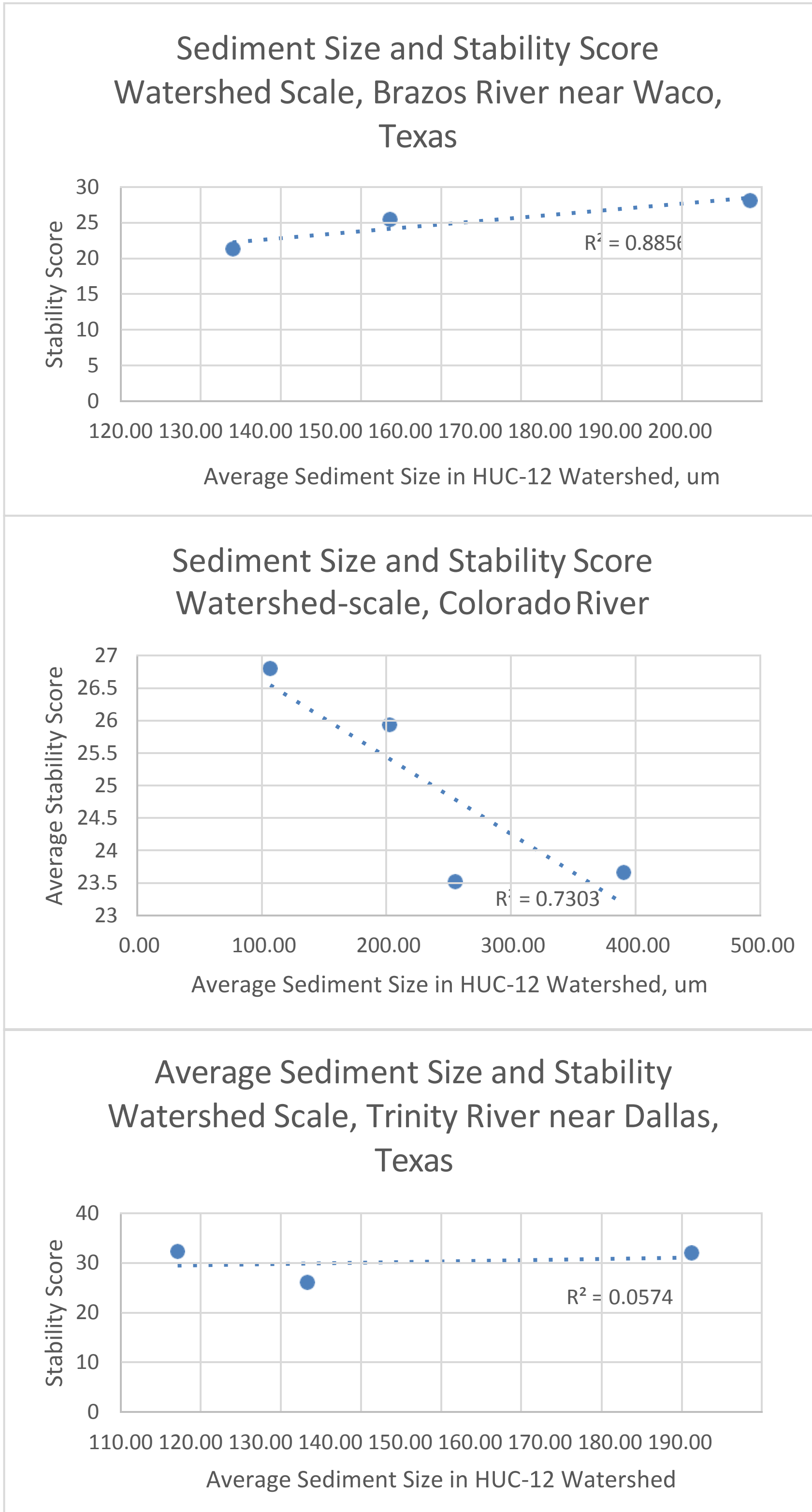

Figure 92: Average sediment size versus stability at watershed scale.

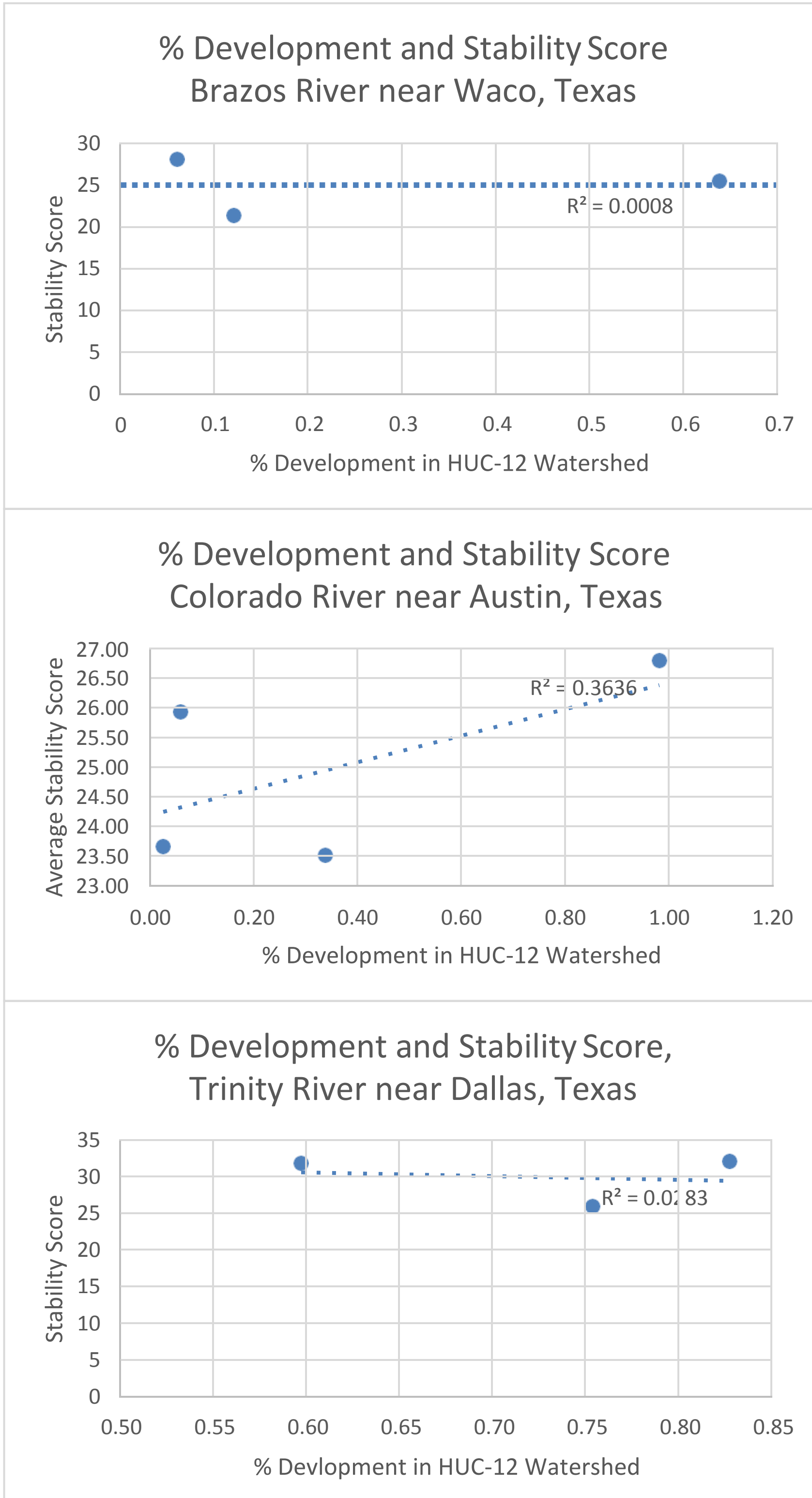

Figure 93: Comparison of development in watershed and stability scores in three study rivers.

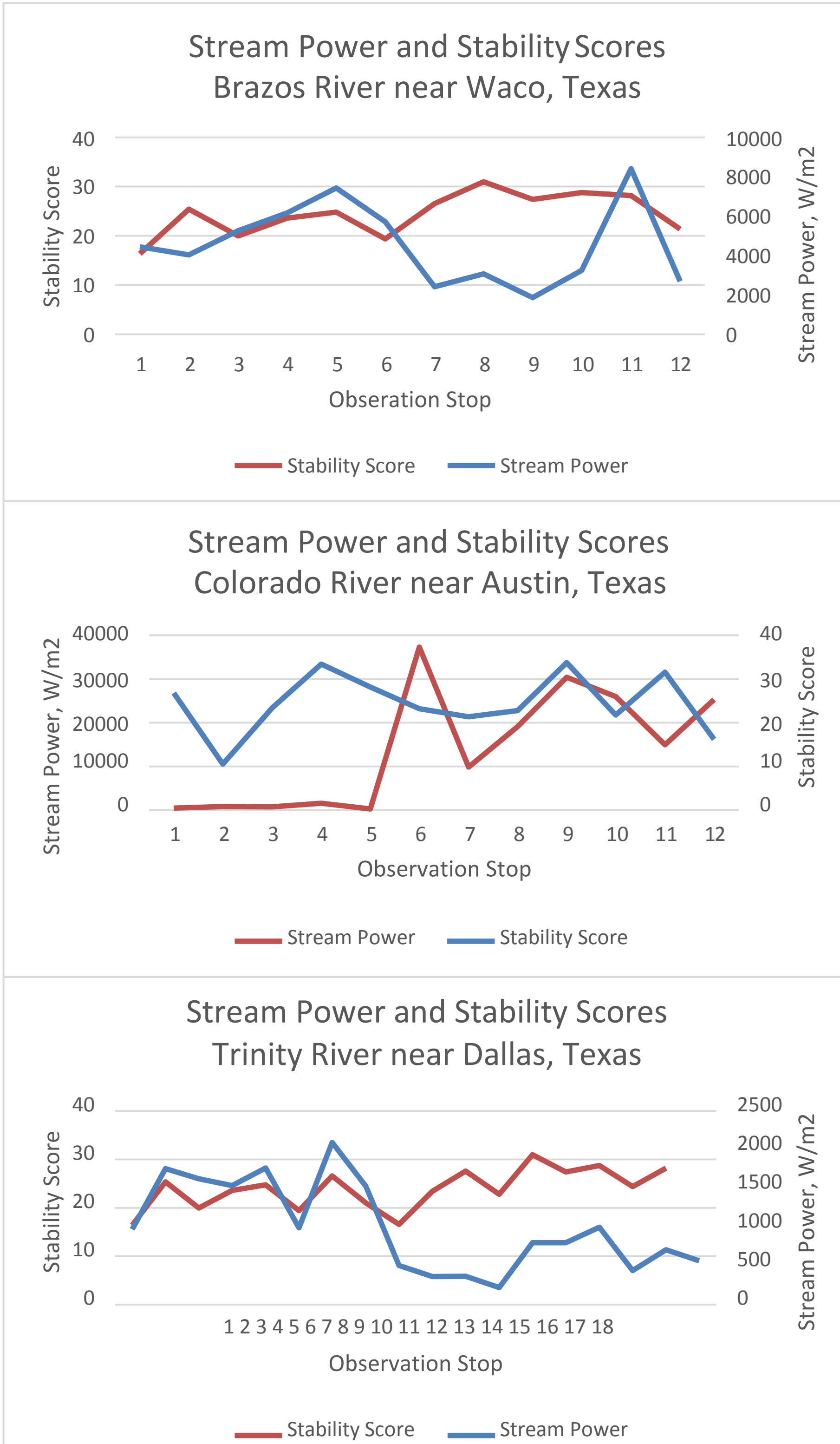

Figure 94: Comparison of stream power and stability values. Notice that even when the values do not directly overlap, changes in one mirror changes in the other.

6.6 Proposed Stability Assessment

This study aims to use a previously established assessment to determine channel stability upstream and downstream of urbanization on each of three Coastal Plain rivers, and to recommend adjustments to stability assessments to make them more applicable to Coastal Plain Rivers. Where stability is defined as the tendency of a river channel to adjust its channel at a rate comparable to others in similar climate and geology, any assessment of channel stability must consider those variables most relevant to the region and modern modifications. The presence alone of anthropogenic modification may not indicate stability level. One should note, however, whether a channel rated as very stable is so because of stabilization features which actively prevent migration and erosion or because the channel is naturally transporting an adequate amount of material for its channel and, in turn, the channel is naturally capable of supporting the river flow regime. The modified Johnson et al. (1999) method, developed by Doyle, et al. (2000) offers an easy to use and efficient method of assessing channel stability based upon morphological indicators. Simple modification should be made to the ranking system for clarity in reporting; higher scores on a stability assessment should indicate higher stability, not lower. Utility of shear stress ratios is very useful for quantifying channel stability but may be difficult to calculate for general practitioners. Stream power offers an alternative for quantifying channel stability that is easily calculated and can be determined for bankfull stage to ensure continuity of calculations when field work must be performed over several weeks, when the river may flow at different stages. A new proposed stability assessment is proposed in Tables 20 and 21.

Stability Indicator	**Poor (1-3)**	**Fair (4-6)**	**Good (7-9)**	**Excellent (10-12)**
Bank soil texture (0.6)	Loamy sand to sand; non-cohesive material	Sandy clay to sandy loam	Clay loam to sandy clay loam	Clay and silty clay; cohesive material
Average bank angle (0.6)	Bank slopes over 60% common on one or both banks (unless bedrock banks)	Bank slopes up to 31 degrees or 60% common on one or both banks	Bank slopes up to 27 degrees or 50% common on one or both banks	Bank slopes <18 degrees or 33% on one/both banks or bedrock banks.
Bank cutting (0.4)	Almost continuous cuts, some over 60 cm high; undercutting, sod-root overhangs, and side failures frequent	Significant and frequent; cuts 30 to 60 cm high; root mat overhangs	Some intermittently along channel bends and at prominent constrictions; raw banks may be up to 30 cm	Little or none evident; infrequent raw banks less than 15 cm high generally
Mass wasting or bank failure (0.8)	Frequent and extensive mass wasting; the potential for bank failure as evidenced by tension cracks, massive undercuttings, and bank slumping is considerable; channel width is highly irregular and banks are scalloped	Evidence of frequent and/or significant occurrences of mass wasting that can be aggravated by higher flows, which may cause undercutting and mass wasting of unstable banks; channel width quite irregular and scalloping of banks is evident	Evidence of infrequent and/or minor mass wasting; mostly healed over with vegetation; relatively constant channel width and minimal scalloping of banks	No or little evidence or potential or very small amounts of mass wasting; uniform channel width over the entire reach
Bar development (0.6)	Bar widths are generally greater than one-half the stream width at low flow; bars are composed of extensive deposits of fine particles up to coarse gravel with little to no vegetation	Bar widths tend to be wide and composed of newly deposited coarse sand to small cobbles and/ or may be sparsely vegetated	Bars may have vegetation and/or be composed of coarse gravel to cobbles, but minimal recent growth of bar evident by lack of vegetation on portions of the bar	Bars are more mature, narrow relative to stream width at low flow, well vegetated and composed of coarse gravel to cobbles

Table 7: Modified Doyle et al. (2000) Assessment of Channel Stability Based on Morphological Indicators

Table 21: Modified Doyle et al. (2000) Stability Assessment

Stability Indicator	Poor (1-3)	Fair (4-6)	Good (7-9)	Excellent (10-12)
Debris-jam potential (0.2)	Moderate to heavy accumulations of various size debris present; debris-jam potential significant	Noticeable accumulation of all sizes; moderate downstream debris potential possible	Small amounts of debris present; small jams could be formed	Debris or potential for debris in channel is negligible
Obstructions, flow deflectors, and sediment traps (0.2)	Frequent and often unstable, causing a continual shift of sediment and flow; traps are easily filled causing channel to migrate and/or widen	Moderately frequent and occasionally unstable obstructions cause noticeable erosion of the channel; considerable sediment accumulation behind obstructions	Present, causing cross currents and minor bank and bottom erosion	Rare or not present
Channel-bed material consolidation and armoring (0.8)	Very loose assortment with no packing	Loose assortment with no apparent overlap	Moderately packed with some overlapping	Assorted sizes tightly packed, overlapping, and possibly imbricated
X’: Difference between stream power values at current site (x) and site upstream, W/m^2 (1.0)*	X’ ≥ 1.5x	1.5x > x’ ≥ x/2	x/2 >x’≥ -(x/2)	X’ < -(x/2)

*** If site is the farthest upstream, use the next row for assessment:**

Table 21, cont'd: Modified Doyle et al. (2000) assessment for channel stability.

X": Difference between stream power values at current site (x) and site downstream, W/m² *(1.0)*	X" < -(x/2)	x/2 >x"≥ -(x/2)	1.5x > x" ≥ x/2	X" ≥ 1.5x
Shear Stress Ratio (1.0)	**$\tau_o/\tau_c > 2.5$**	**$1.5 < \tau_o/\tau_c < 2.5$**	**$1.0 < \tau_o/\tau_c < 1.5$**	**$\tau_o/\tau_c < 1.0$**

Practitioners may opt to use only shear stress ratio or stream power as a quantitative assessment, or both criteria. So long as the same criteria are used for all assessment sites, either method is acceptable. Calculations for stream power should be based on bankfull zone calculations. This ensures continuity of dimensions and hydraulic characteristics. Bankfull zone is defined as the region extending from the threshold of the main channel and the adjacent step sufficiently wide to sustain permanent structures to the threshold of the main floodplain. Bjerklie (2007) offers simple empirical equations for estimating bankfull velocity and discharge of remotely sensed rivers, which may be used alone or in conjunction with field measurements.

As defined by Doyle et al. (2000), cross-sectioned average boundary stress (**τ_o**) exerted on the bed is $\tau o = \gamma RS$, where γ is the unit weight of water, R is the hydraulic radius, and S is the energy slope, which at bankfull flow can be assumed to be the bed slope. Critical shear, τc, the shear at which bed motion is initiated, is given by

$\tau c = \tau c^*(\gamma s-\gamma)D$, where τc^* is the dimensionless Shields parameter for entrainment of a sediment particle of size D, and γs and γ are the unit weight of sediment and water, respectively. Although D50 is conventionally used for D, average sediment size may be used, so long as the same parameter is used throughout.

6.6 Conclusion

Urbanization is known to alter river channel morphology, which can lead to degradation of water quality and ecological health of the channel, as well as extensive restoration or maintenance efforts. By assessing the effects of urbanization on the geomorphic channel stability of three major rivers in the Gulf Coast region, this study contributes to the understanding of the impact of urbanization on watersheds and aids in prediction of urban river activity in this region. This will allow for more timely and efficient restoration and management efforts as urban centers increase in the future.

As urbanization is predicted to affect most rivers in Texas in the future, the ability to predict and remediate the effects of urbanization has far-reaching consequence. For instance, some landowners in Texas hold riparian rights to streams that border their property. Riparian rights grant access to water to landowners whose property is in contact with a river or natural lake. Generally, tracts of land bounded by streams will slightly evolve as the river migrates gradually, with little concern to landowners (Morgan, per. comm. 2018), but in cases of avulsion, a river may change course significantly, altering property lines. This is, understandably, of great concern to landowners. As urbanization is linked to higher streamflow resulting from increased runoff, it is reasonable to suspect a greater threat of avulsion as a result of widespread urbanization.

Additionally, one should consider the implications of the adjustments of river channels in Texas, where navigable waters are public property. A stream is “navigable” if it retains an average width of 30 feet from the mouth upstream. Importantly, the entire stream bed is considered in this measurement, not the water alone. The stream bed, in turn, is defined by the Texas Supreme Court as "that portion of its soil which is alternately covered and left bare as there may be an increase or diminution in the supply of water, and which is adequate to contain it at its average and mean stage during an entire year, without reference to the extra freshets of the winter or spring or the extreme drouths of the summer or autumn" (Texas Parks and Wildlife Department). The streambed is specifically that land between the "gradient boundary" on each bank. The gradient boundary is defined by the Texas Supreme Court as "a gradient of the flowing water in the stream, and is located midway between the lower level of the flowing water that just reaches the cut bank and the higher level of it that just does not overtop the cut bank” (Texas Parks and Wildlife Department). As difficult as these locations may be to define in any situation, channel adjustment resulting from the effects of urbanization will further complicate these determinations.

The effects of urbanization on river morphology vary by location. The type and degree of urbanization must be considered, along with local geology, climate, and topography. Studies of the effects of urbanization on river channel morphology have been performed at several locations (Graf, 1975; Arnold, et al., 1982; Jeje and Ikeazota, 2002; Deacon et al., 2005; Grable and Hardin, 2005; McBride and Booth, 2005; Segura and Booth., 2010; Nowell, et al., 2012; Cockerill, et al., 2017; Wu, et al., 2017; Yousefi, et al., 2017; Vizzari et al., 2018; Weil et al., 2018), but few have been conducted in regions with the climate (Köppen-Geiger Cfa: warm temperate, fully humid, hot summer), geology (predominantly Cretaceous-aged limestone and shale, some sandstone), and topography of the Gulf Coast region of the United States. Further, the effects of changes in land cover, such as that which occurs with urbanization, have been studied at the scale of plot, field, and small watershed, but have yet to be fully determined at a larger scale (Wilcox et al., 2011).

Given the current growth in population and projections for the region, it is necessary to understand effects of urbanization on the rivers in the Gulf Coast to prepare for fluvial adjustments induced by the rapid expansion of its urban centers. Rivers are dynamic systems, which routinely migrate and adjust form, but in this study an unstable river channel is considered one which is altering its form more rapidly than would be expected for a channel in a similar geologic or climatic region (Doyle et al., 2000). Assessing the effect of urbanization on channel stability will aid in prediction of urbanization impacts and determination of remediation efforts (Doyle et al., 2000).

Projections by the United Nations Department of Economic and Social Affairs (2015) indicate that by the year 2050, 6.3 billion people will live in an urban setting around the world. This number is up 72% from 2011 levels. My study will aid in prediction of urbanization impacts and determination of remediation efforts by assessing the effect of urbanization on channel stability (Doyle et al., 2000). Urbanization is known to alter river channel morphology directly by reducing sediment input and increasing runoff (Leopold, 1968; Hammer, 1972; Graff, 1975; Chin, 2006; Simon and Rinaldi, 2006; Yousefi et al., 2017;) which can lead to degradation (Simon and Rinaldi, 2006), reducing water depth (Jeje et al., 2002) and indirectly altering habitats of native wildlife and vegetation (Butler, 2006). Still, the specific effect of urbanization on stream hydraulics is not well understood (Anim et al., 2018). Channel degradation changes the aesthetic appearance of the channel, and also the ecology, water quality, and efficiency. Anthropogenic modification has already been linked to an increase in nonpoint source pollution (Praskievicz, 2015), toxicity in stream sediment (Nowell et al., 2012; Cockerill, et al., 2017; Wu et al., 2017), and channel and floodplain modification (Leopold, 1968; Hammer, 1972; Graf, 1975; Arnold, et al., 1982; Bledsoe and Watson, 2001; Segura and Booth, 2010).

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CHAPTER VII

CONCLUSIONS

7.1 Introduction

This study investigated the effects of urbanization on the morphological stability of three Gulf Coastal Plains rivers: the Brazos, the Colorado, and the Trinity in Texas. Morphological stability is a broad concept and difficult to define succinctly. I defined a morphologically stable stream as one which maintains its channel form or adjusts it at a rate comparable to other rivers of the same type, climate, and geology. To define channel stability, four approaches were taken. A discussion of these approaches follows.

7.2 Stream Power and Unit Stream Power

The ability of a river to perform work, and more specifically to erode its channel, is quantified by stream power and unit stream power. Stream power (Ω) was calculated by the equation $\Omega = pgQS$ where p is the density of water, g is acceleration due to gravity, Q is discharge and S is channel slope. Unit stream power was calculated by dividing stream power by the width. These factors were assessed as a quantitative evaluation of the stability of each channel.

Each river was traversed for approximately 6 miles upstream and 6 miles immediately downstream of the respective urban center on its banks. 10-15 stops were made for collecting appropriate data for calculating stream power and unit stream power. Bankfull discharge was calculated empirically from field and remote sensing data. Changes to stream power and unit stream power downstream of urbanization were assessed.

Although the Colorado River and Brazos River exhibited increased stream power and unit stream power downstream of urbanization, the Trinity River exhibited decreased stream power and unit stream power. This is evidence that it is not merely the physical changes wrought by urbanization (land cover alteration, channel smoothing, channel engineering) that affect the power of the water, but management of the river and its structures. Future research should endeavor to quantify the relative effects of hydroelectric dams, flood control dams, weirs, and agriculture for a comprehensive overview of their cumulative effects on stream power and unit stream power.

7.3 Bedload Sediment Size

Sediment size is relevant to morphological stability because fine sediment is more cohesive and resistant to erosion, and because sediment size affects lotic habitat and the activities of biogeomorphic drivers. Each river was traversed for approximately 6 miles upstream and 6 miles immediately downstream of the respective urban center on its banks. 10-15 stops were made, and bedload sediment collected at each. The sediment was then dried and sieved. Average and median sediment size for each stop were determined and results compared upstream to downstream.

I offered a review of the effects of biogeomorphology in the lotic environment and the effects of sediment size on water quality and lotic habitat. These three rivers are habitat to a diverse array of stabilizers and destabilizers who are affected by water quality and channel properties.

In the Brazos and Colorado Rivers, average maximum sediment size decreased downstream of urbanization. In the Trinity River, it increased. This may be because the Trinity River is the only river in this study without a dam marking the end of its urbanized reach, and so higher flows transport larger sediment sizes.

7.4 Alteration of Land Cover

Alteration of land cover is the most impactful change made to a watershed and I hypothesized that stream channels downstream of high-impact development would exhibit low stability, high stream power, and increased sediment size. The HUC-12 watershed for each study reach was investigated in ArcGIS and its land cover components assessed. These were compared to changes in stream power, stability, and sediment size. No discernable relationship was discovered, indicating that the changes exhibited by a river channel are the function of not only the immediate sub-watershed, but the larger drainage basin. Further research should be performed on entire drainage basins for a more comprehensive assessment of how land cover alters the hydraulic properties of a river.

7.5 A Classification System

The most widely used system of river classification, the Rosgen system, is often criticized for its ineffectiveness for classifying low-gradient coastal plains rivers. I give an overview of classification systems and a thorough discussion of Rosgen's system and the concept of bankfull stage. I propose a new classification system for low-gradient rivers and introduce the concept of bankfull zone, to replace bankfull stage in classification.

7.6 Morphological Assessment by Qualitative Indicators

In addition to stream power, unit stream power, and sediment size, qualitative indicators of morphological stability are considered. Each river was traversed for approximately 6 miles upstream and 6 miles immediately downstream of the respective urban center on its banks. 10-15 stops were made, and morphological channel stability was assessed using qualitative indicators. These were based on an established scoring system of channel instability in which higher scores indicate greater instability than lower scores. Factors considered included vegetative cover, presence of mass movement, flow disruptors, bank angle, sediment size, bank scalloping and bank cutting.

Each river in this study exhibited greater instability downstream of urbanization. The Trinity River in Dallas exhibited a rapid recovery as it flowed through the Great Trinity Forest, however. This indicates the importance of natural land cover in maintaining the morphological stability of a river channel. The Brazos and Colorado Rivers exhibited greater stability downstream than upstream of urbanization, but the difference was not as great as the Trinity. This is further evidence that the management of the river should be included in an assessment of its stability, as well as its physical changes.

7.7 Conclusion

The morphological stability of three rivers in the coastal plains of Texas was assessed using quantitative and qualitative indicators. All three exhibited reduced stability downstream of urbanization, though the degree of instability varied widely based upon river and watershed management. Future researchers should investigate the effects of land cover in larger watersheds (perhaps HUC-8) on the entire length of each river and consider the effects of potential urban heat islands and land or river management. Future researchers should also refine the classification system proposed and determine a method by which management can be quantified and accounted for in classification.

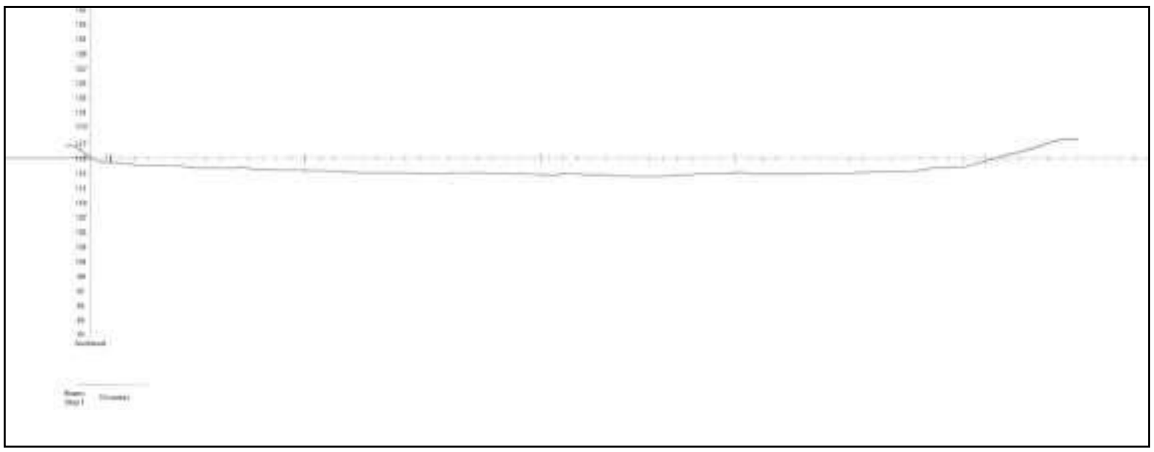
APPENDIX A

CHANNEL CROSS SECTIONS OF EACH OBSERVATION POINT ON THE

BRAZOS, COLORADO, AND TRINITY RIVERS IN TEXAS

Brazos River

BR01



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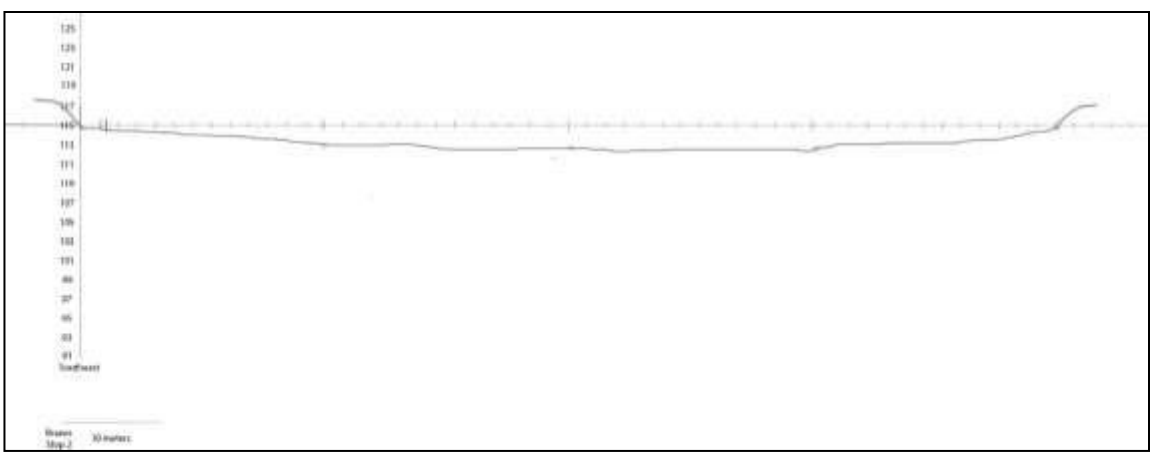

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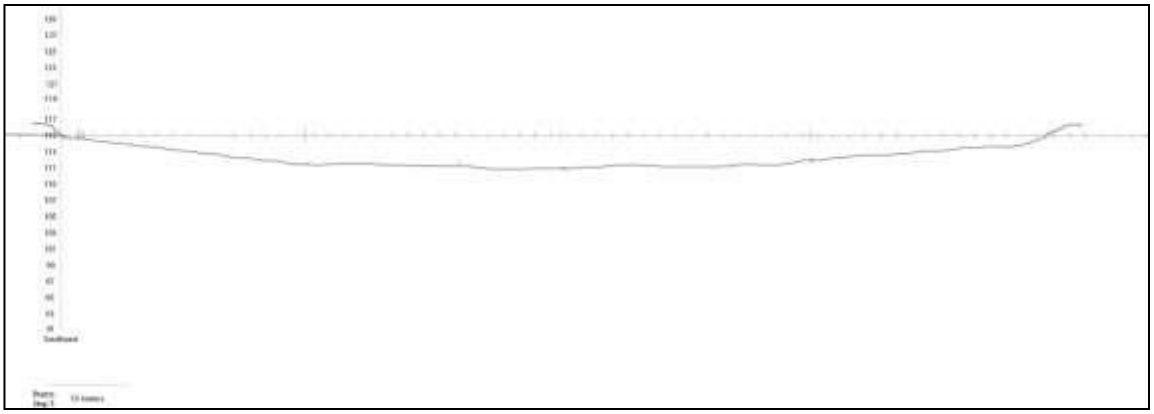

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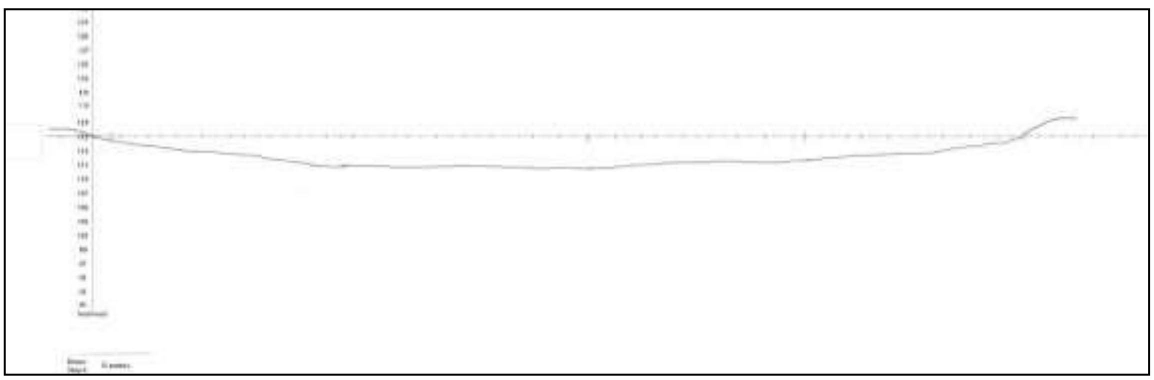

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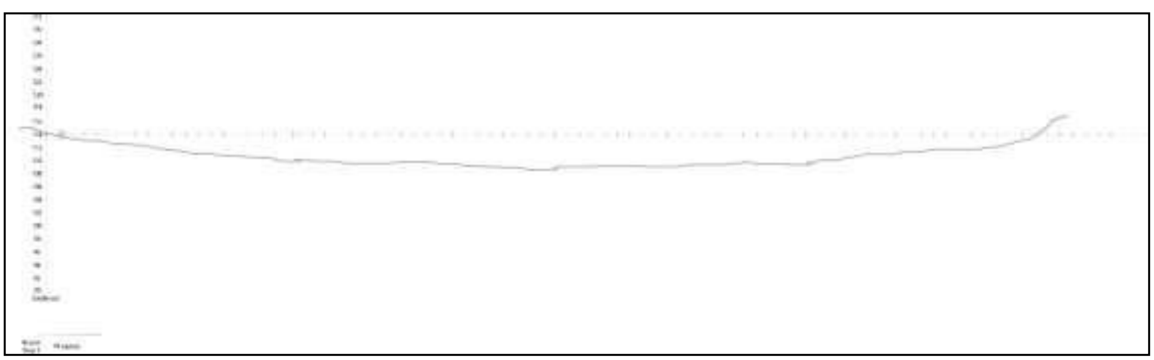

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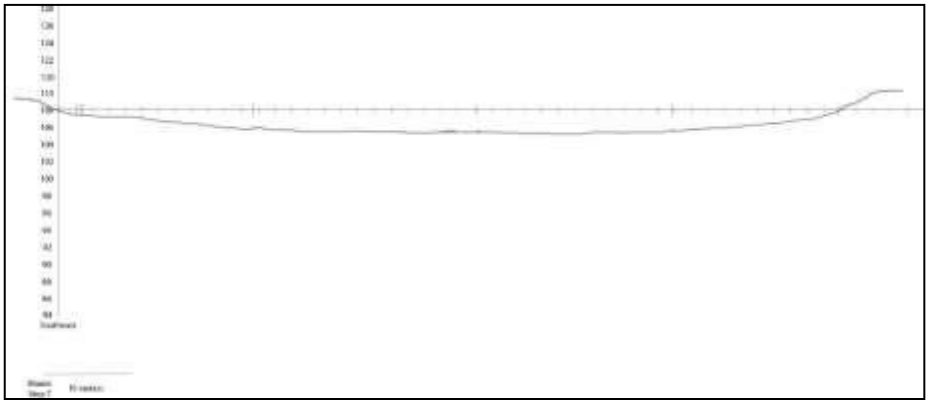

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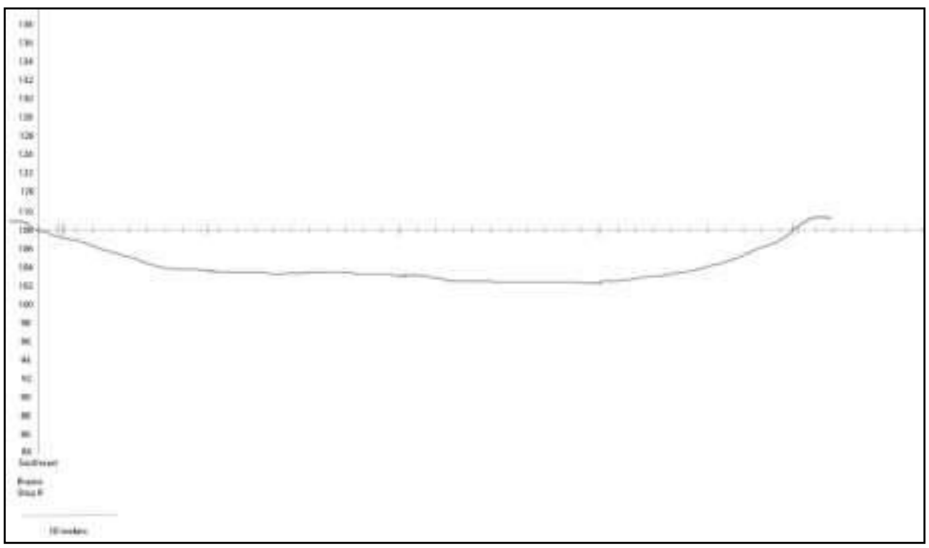

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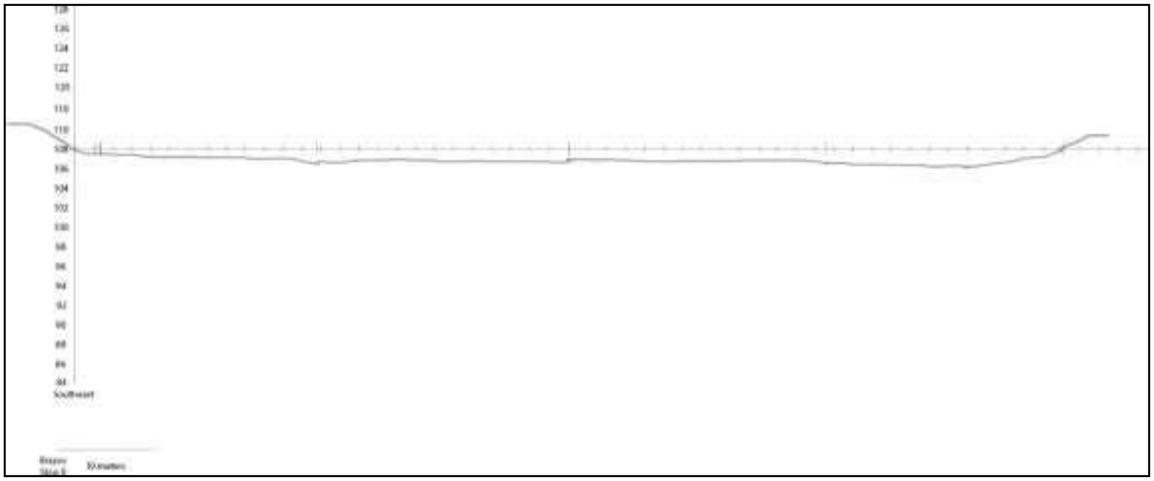

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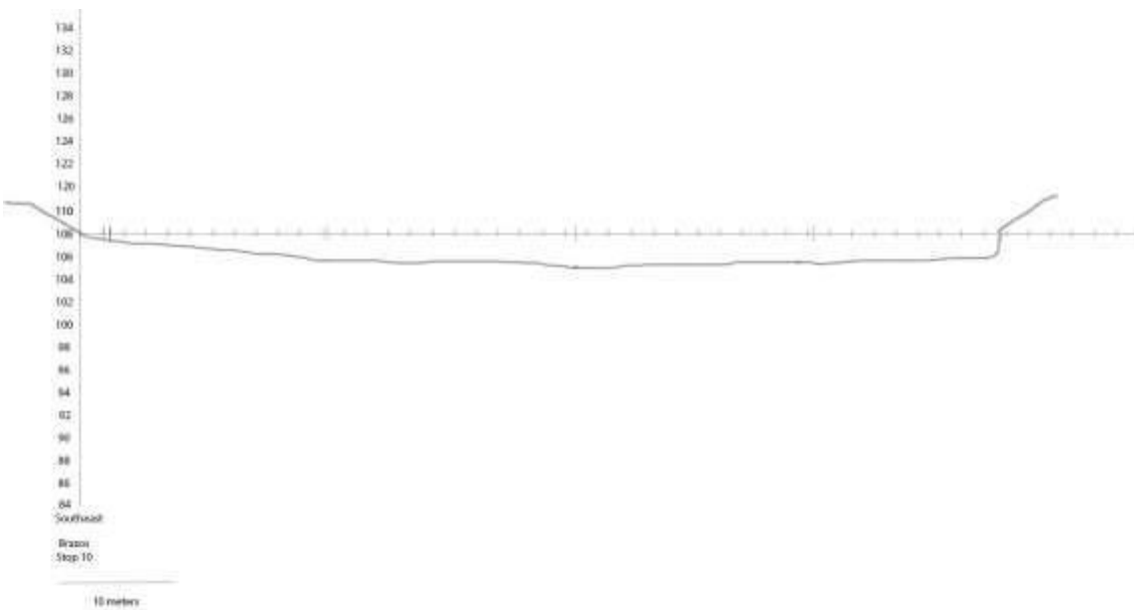

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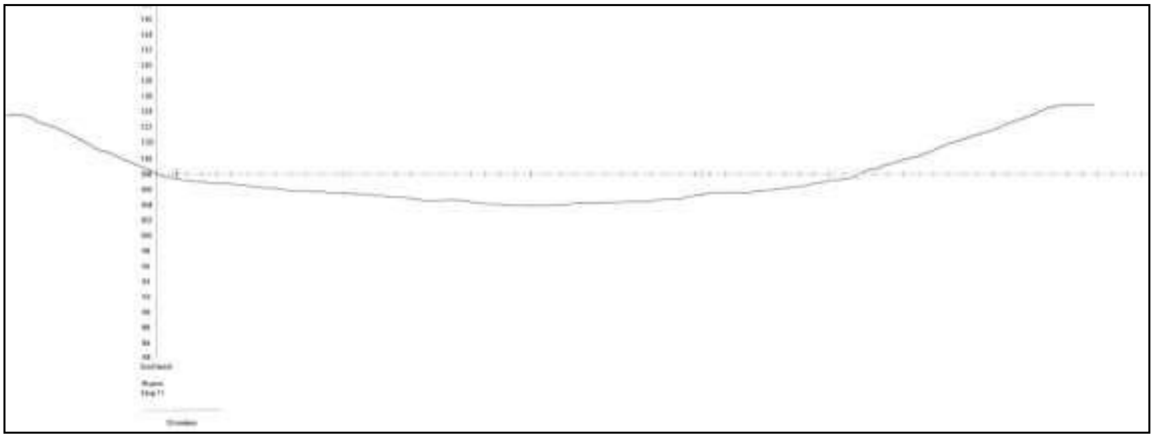

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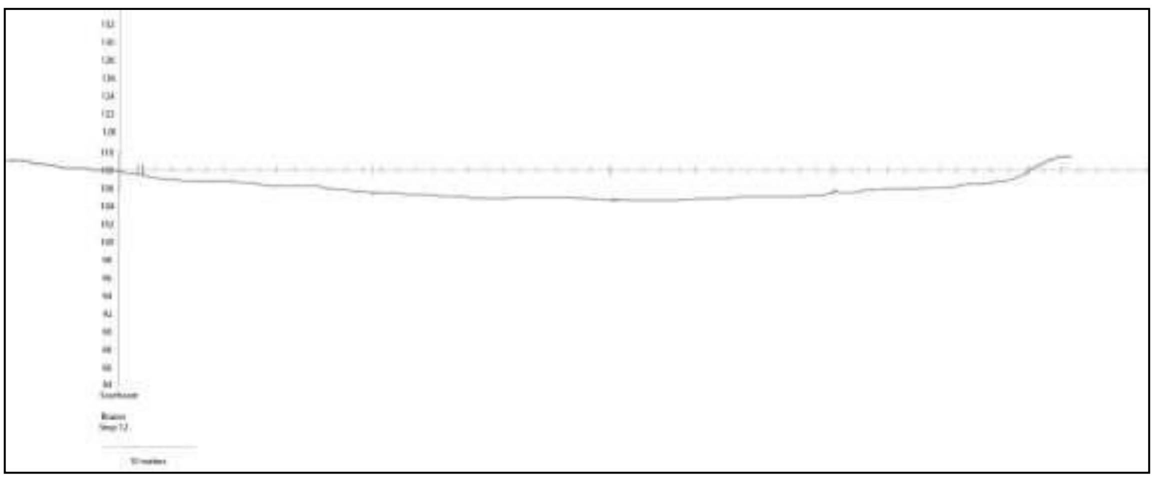
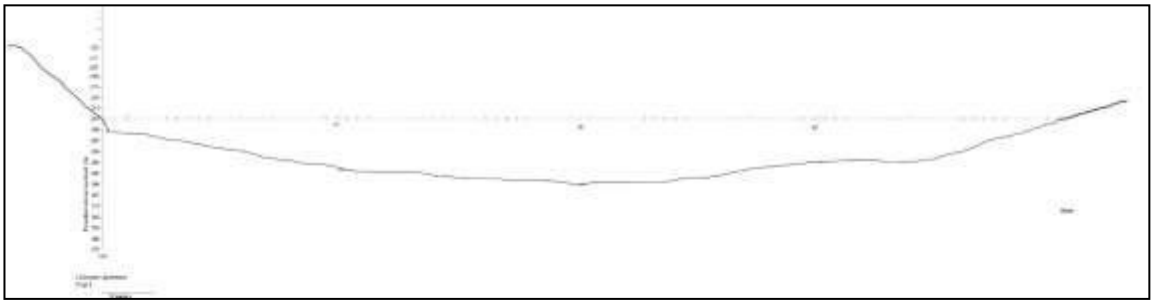


Colorado River

CR01



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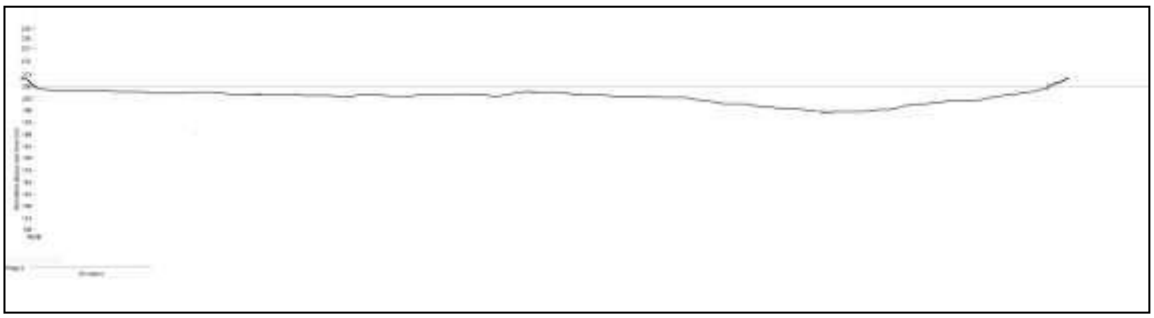

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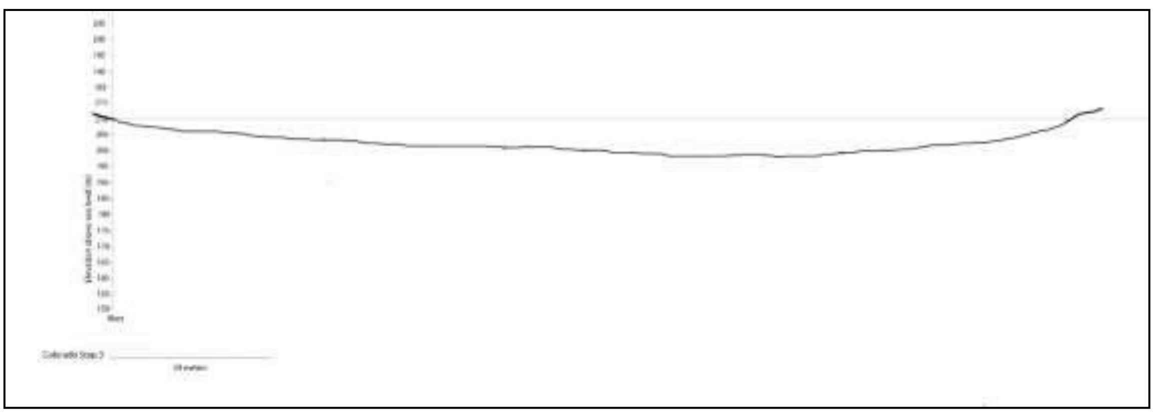

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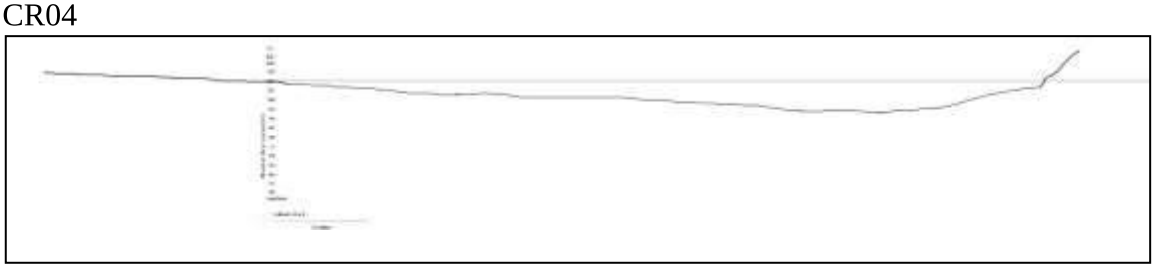

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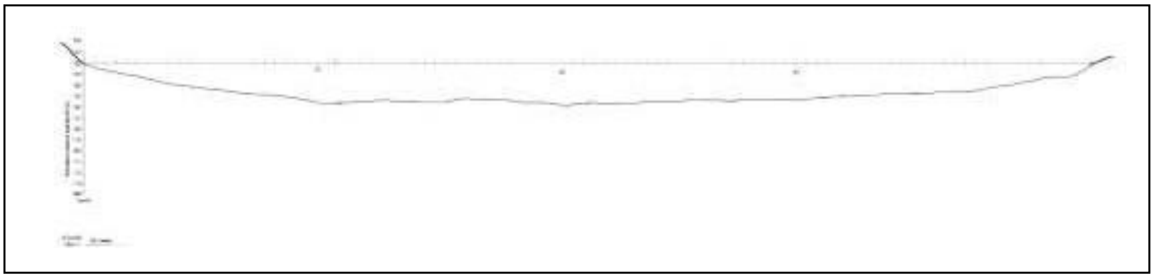

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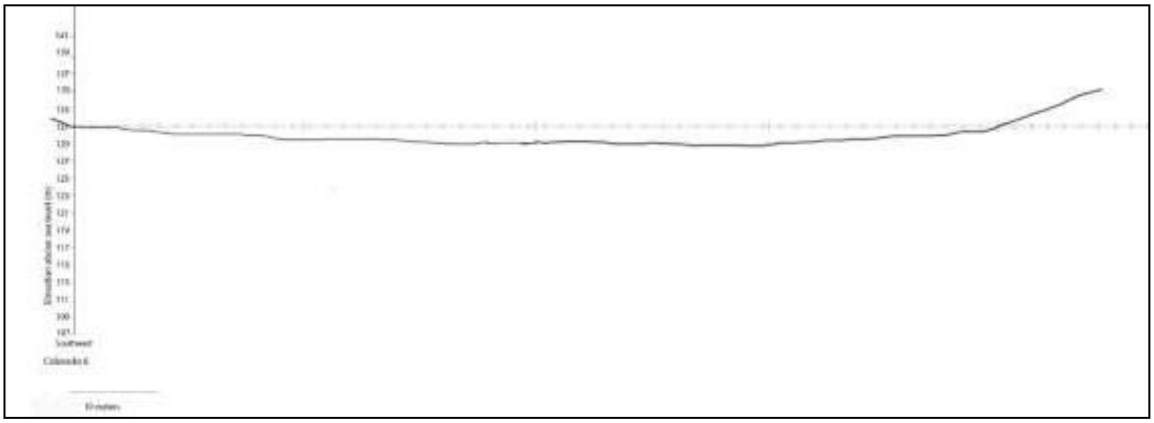

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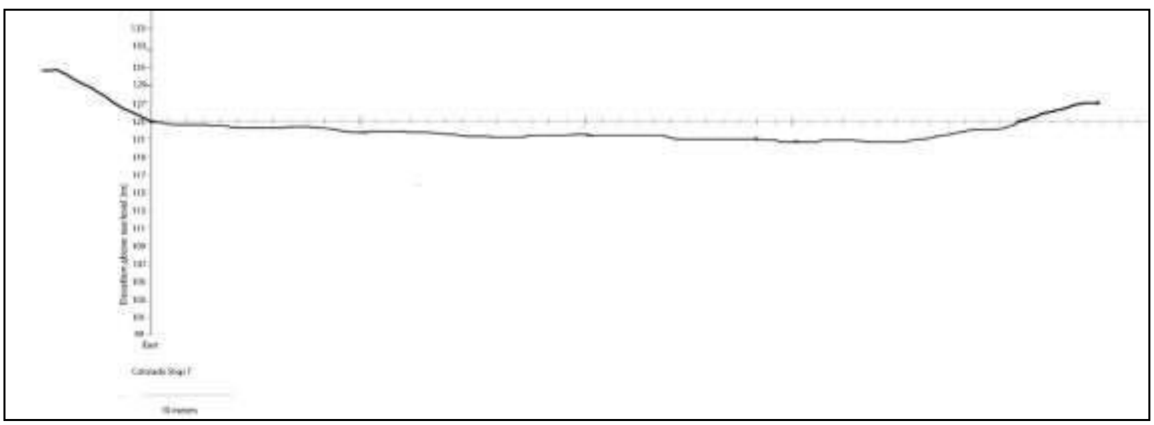

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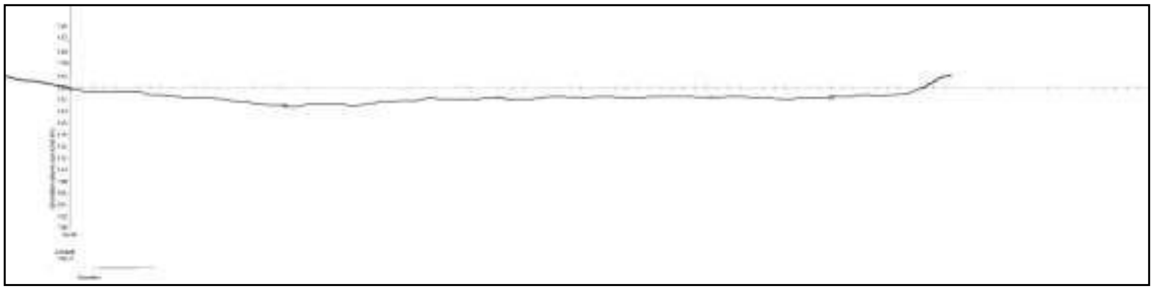

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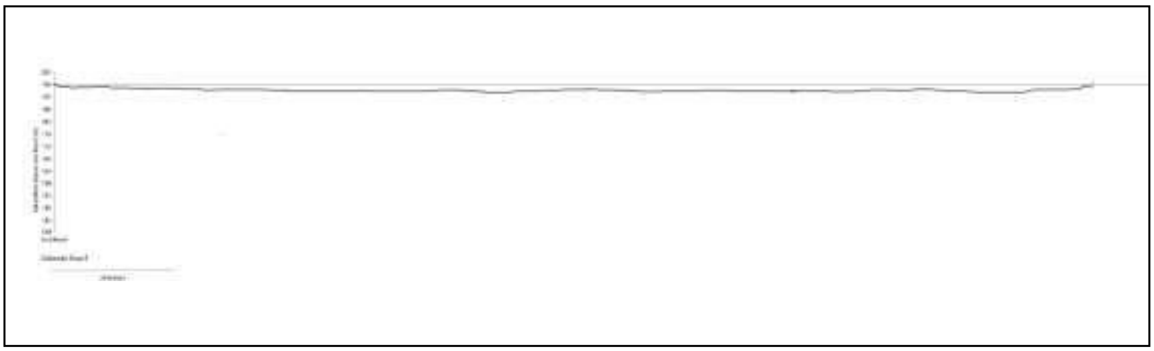

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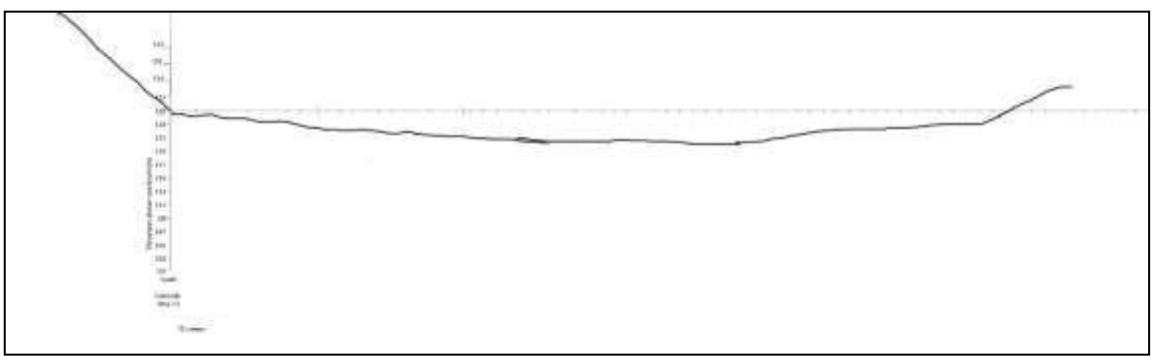

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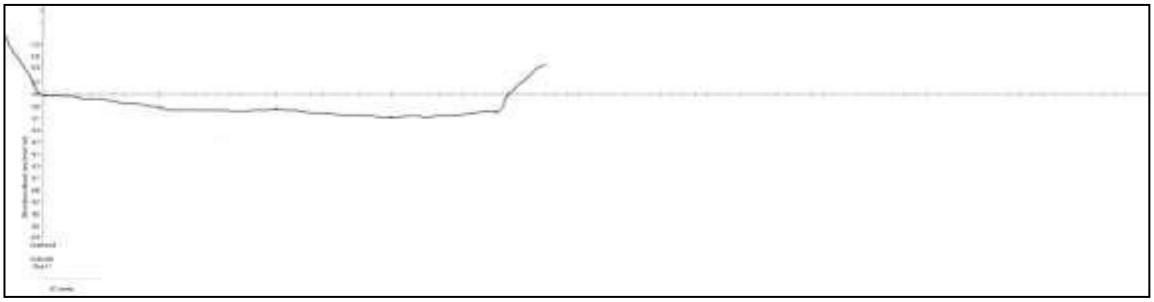

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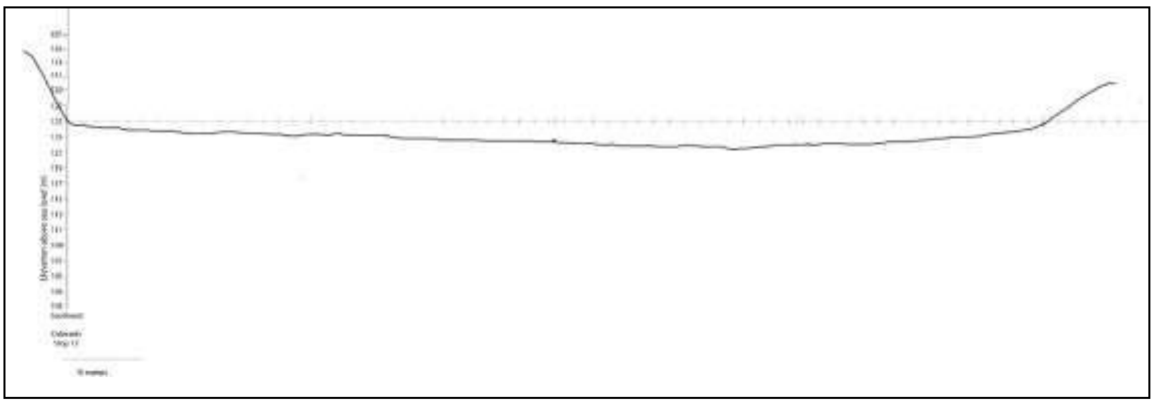

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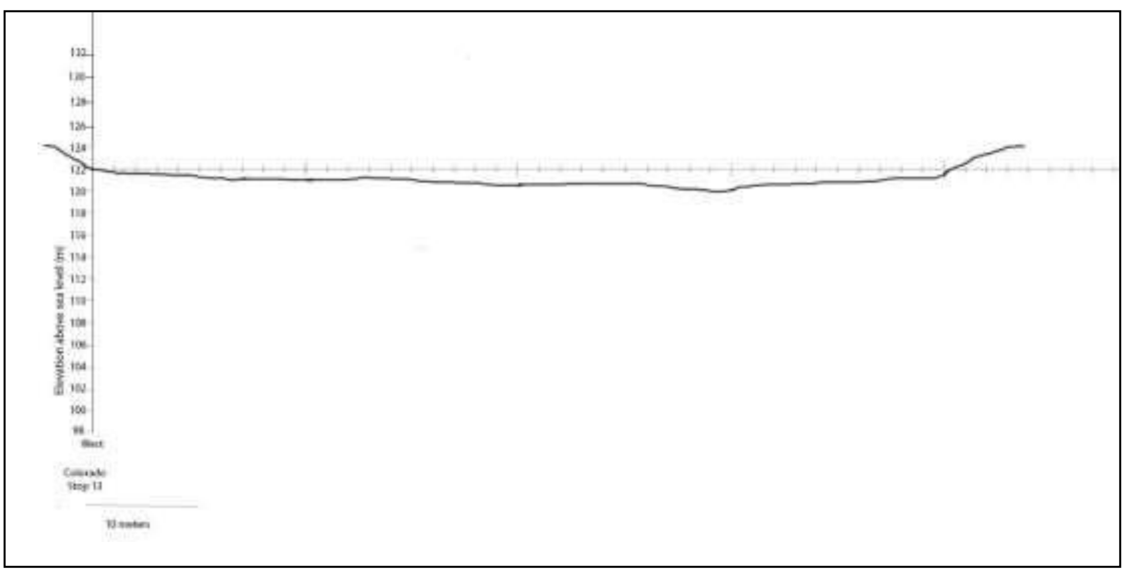

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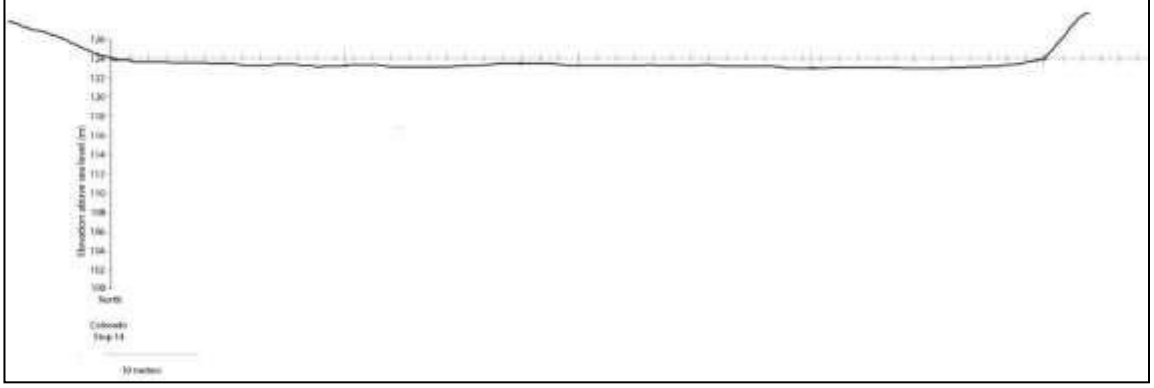

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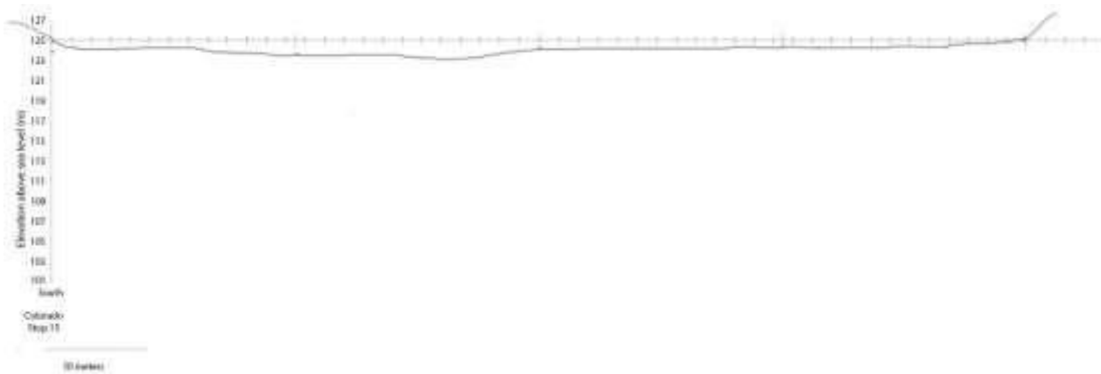
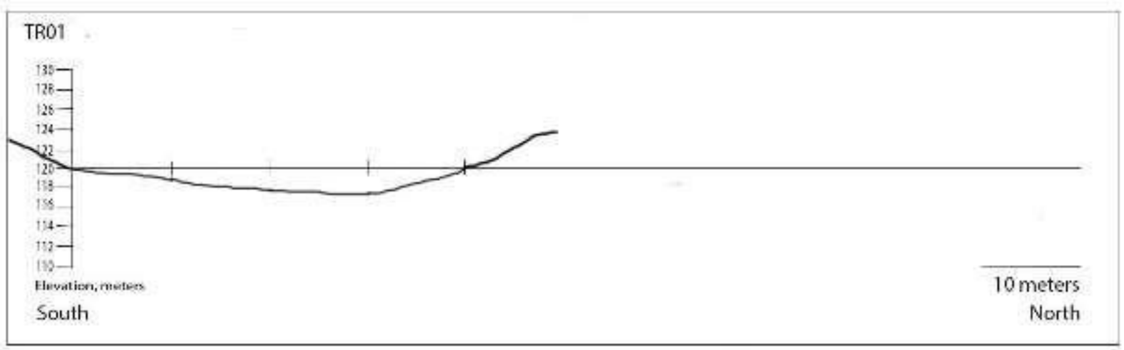


Trinity River

TR01



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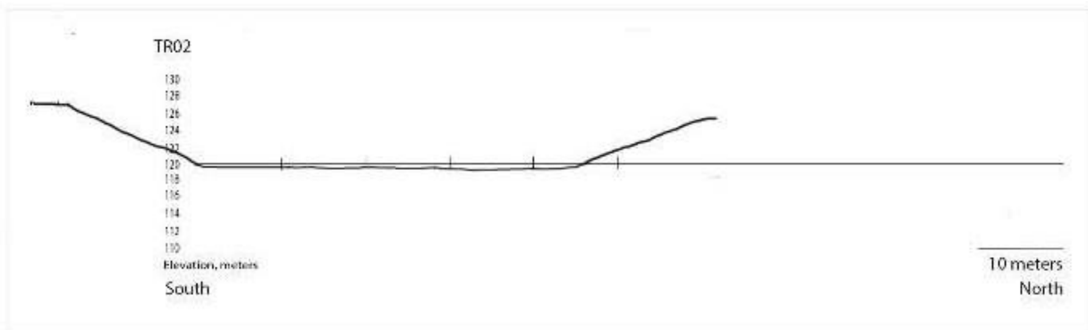

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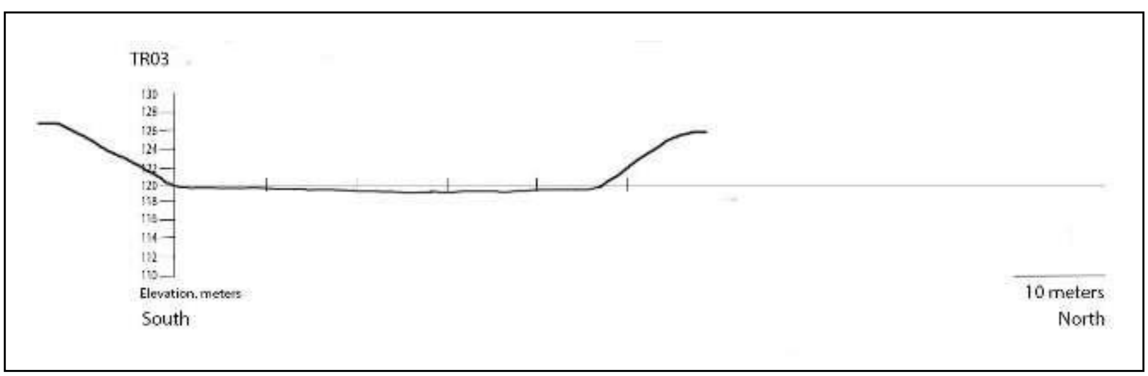

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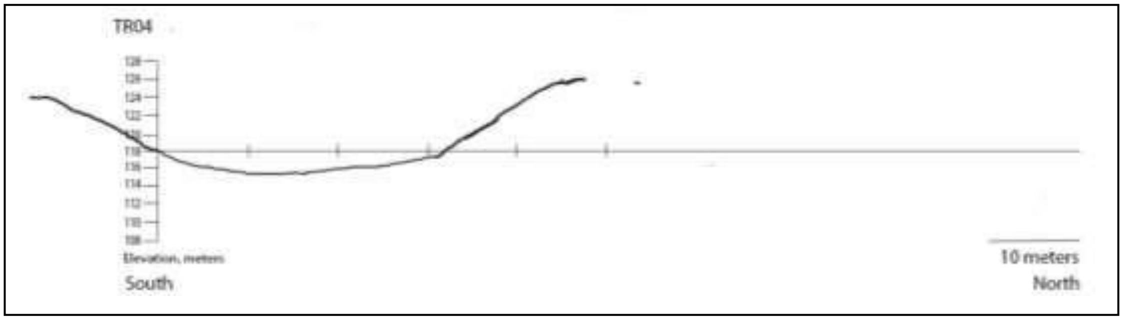

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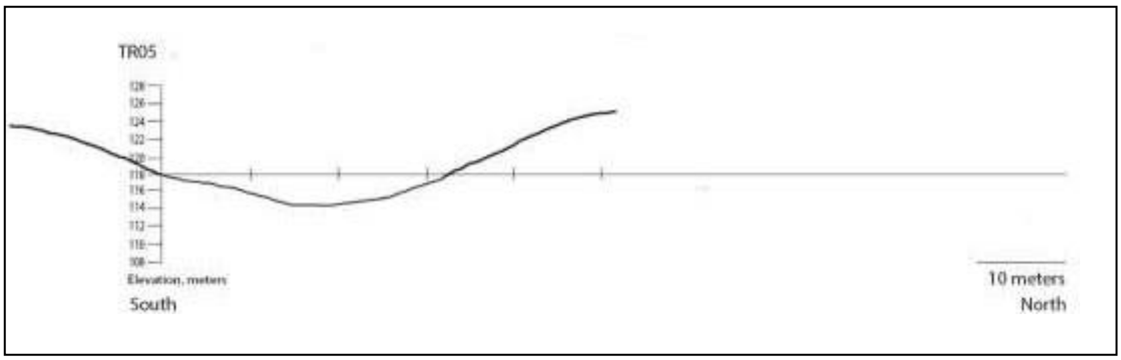

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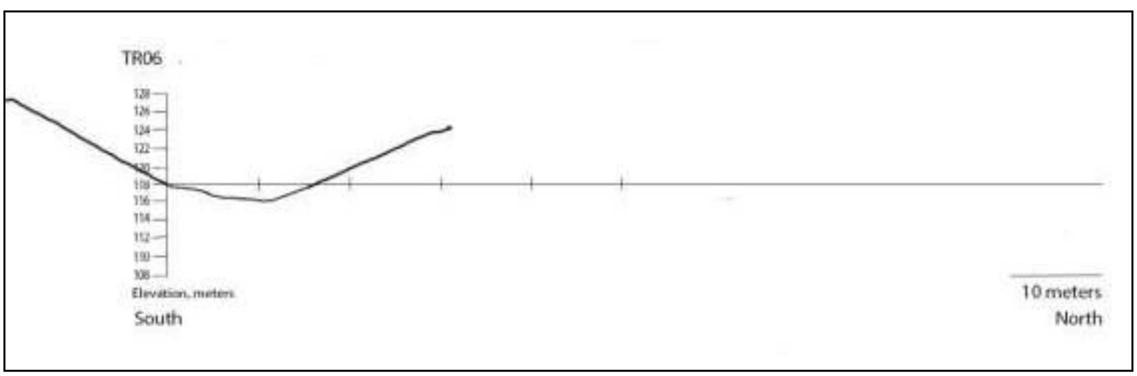

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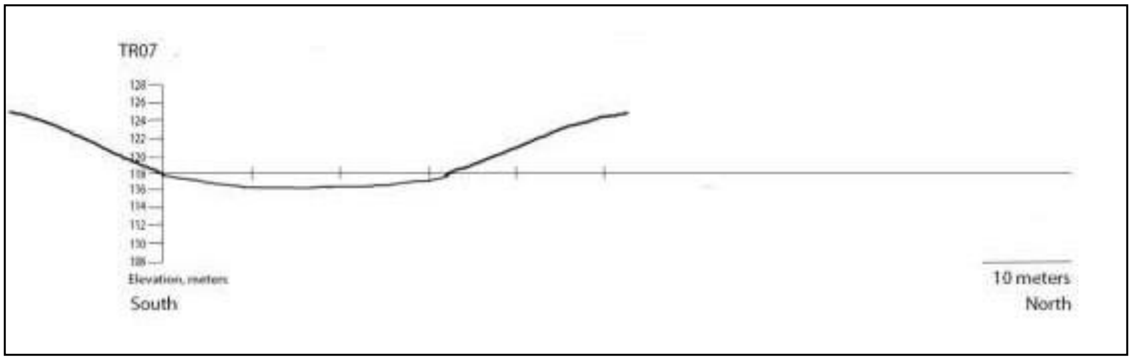

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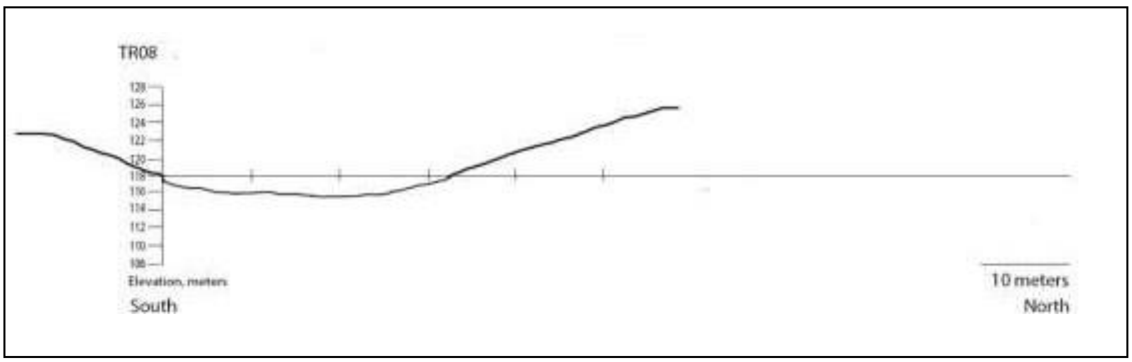

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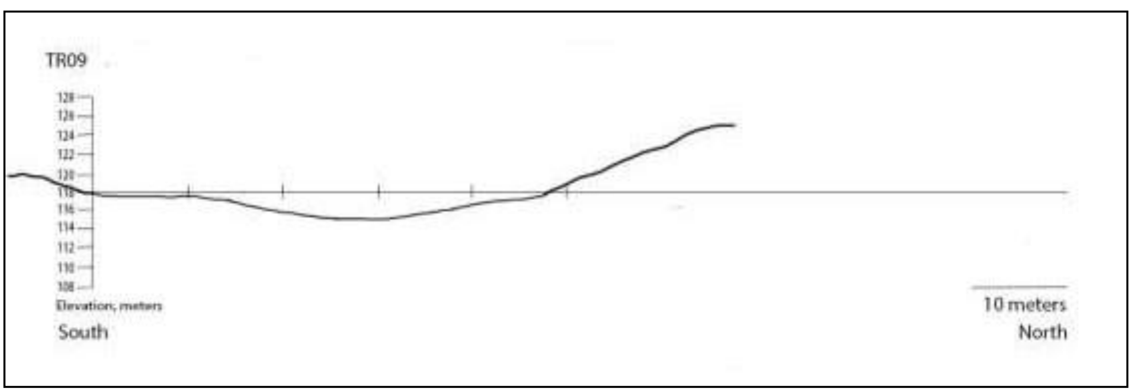

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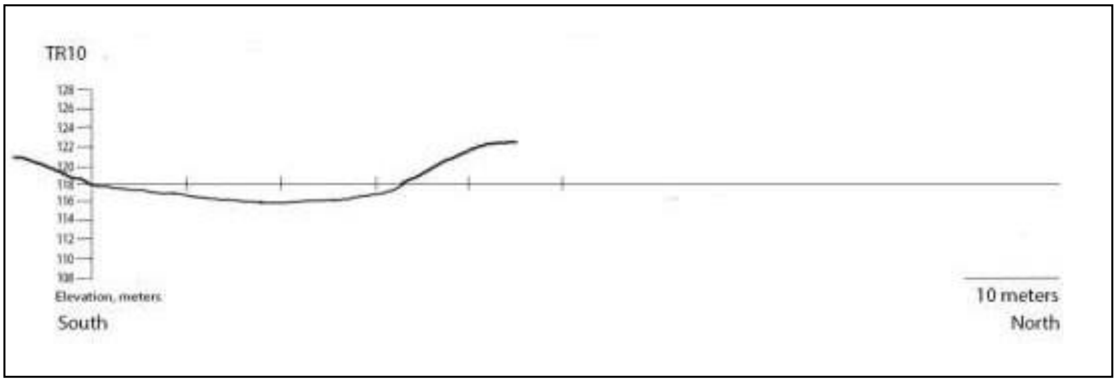

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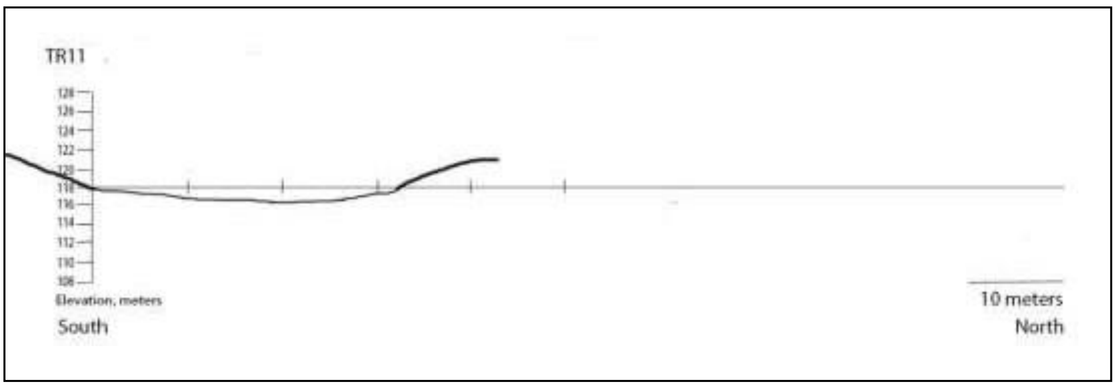

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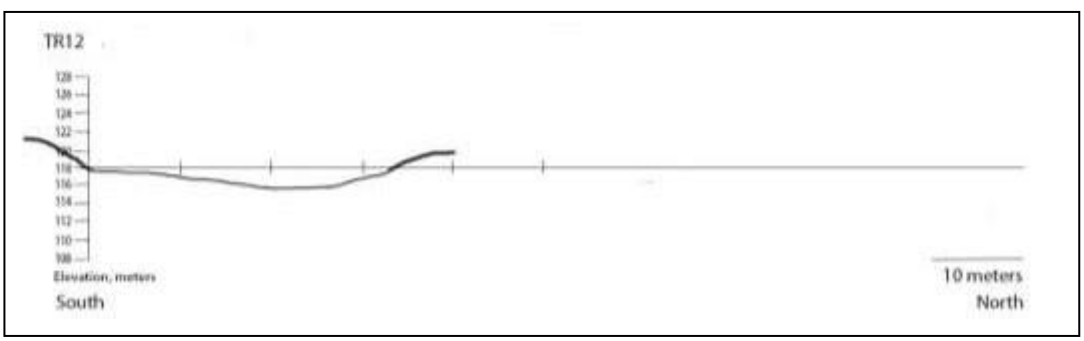

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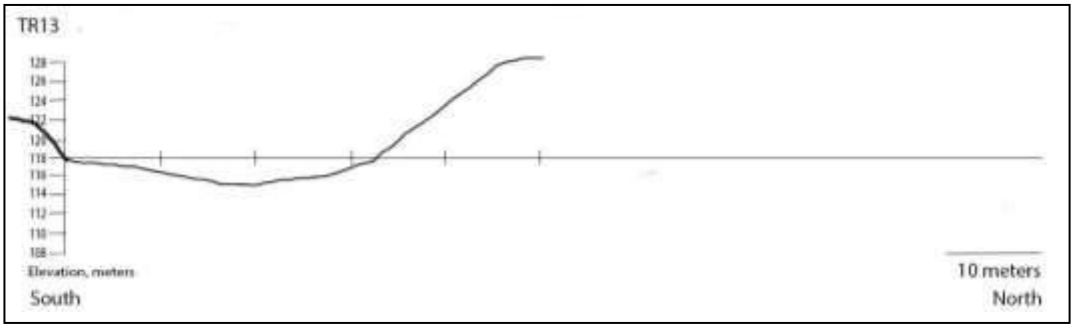

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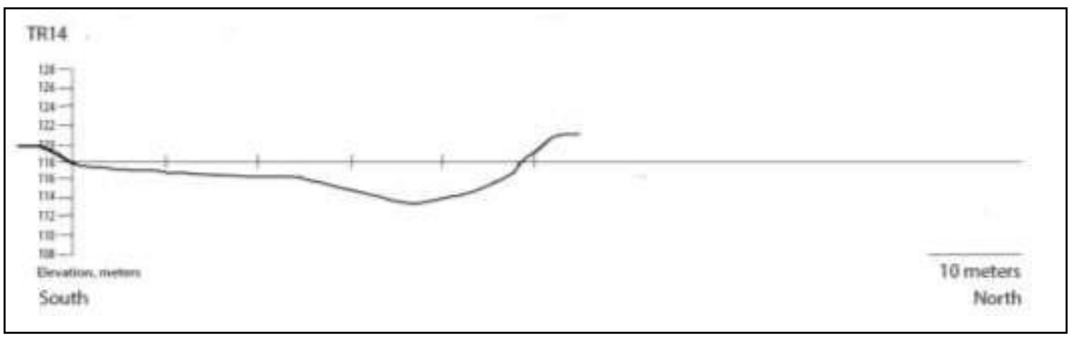
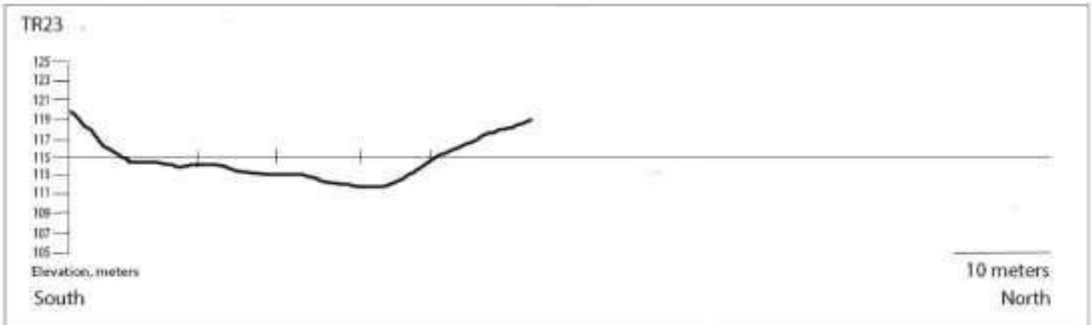


TR22

TR23



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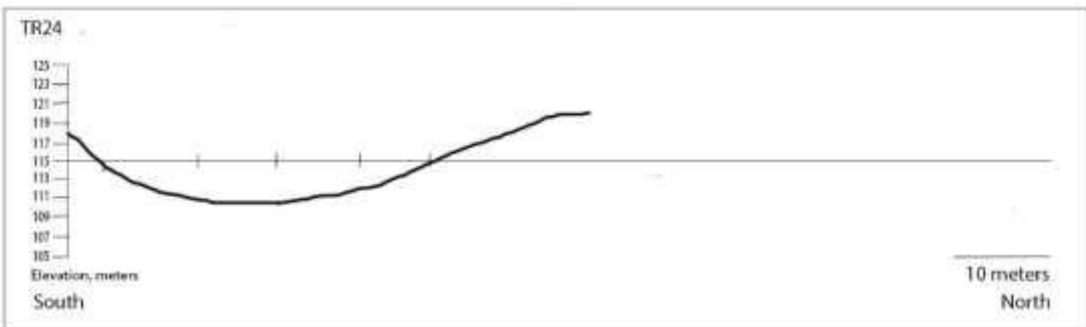

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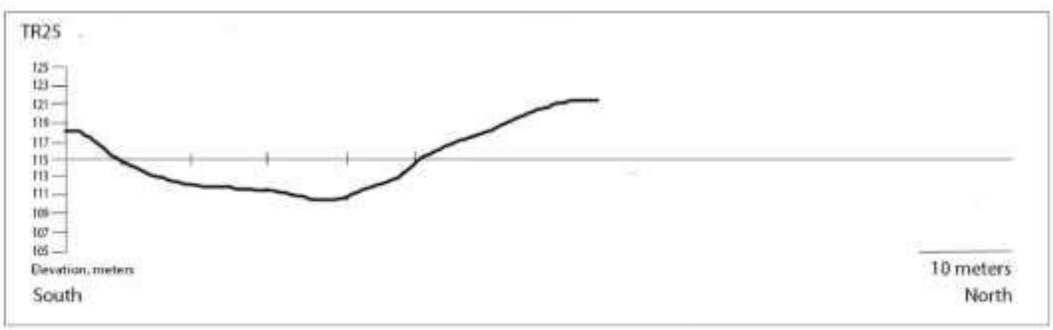

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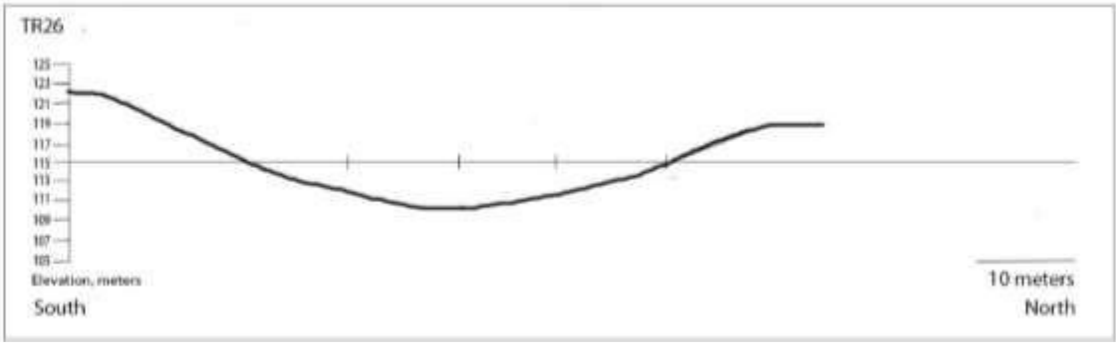

TR26
121
117
113
111
107
Elevation, meters
10 meters
South
North

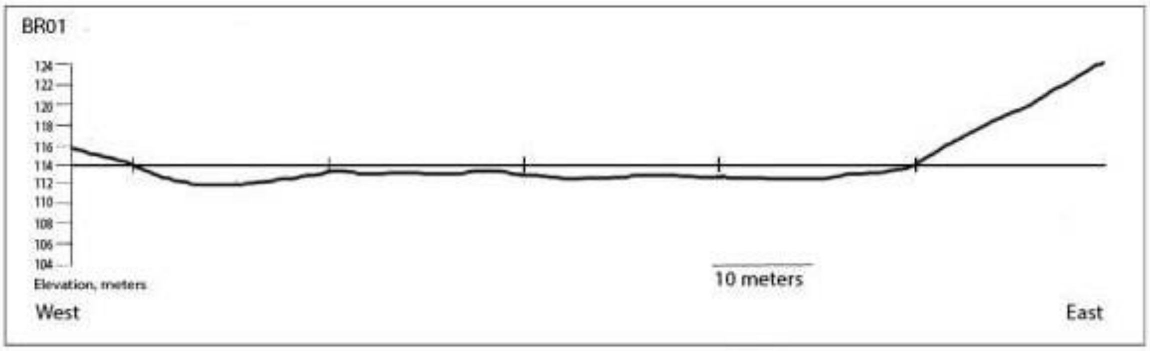
APPENDIX B

ASSESSMENTS OF CHANNEL STABILITY USING MORPHOLOGICAL INDICATORS: BRAZOS RIVER NEAR WACO, TEXAS

A six-mile stretch of the Brazos River was studied, beginning at Lake Shore Drive (FM 3051) spanning the Brazos River and ending upstream near Buster Chatham Road. Nine sites were sampled along this segment, to discern the stability of the Brazos River upstream of the urbanization of Waco, Texas. At each site, a localized assessment of channel stability was made based upon the Modified Johnson et al. (1999) Method for Assessing Channel Stability, developed and used by Doyle et al. (2013).

BR01:

BR01 was located in the Brazos River near Buster Chatham Rd. A cross section of BR10 is presented below.



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 4- Good.
2. **Average Bank Angle (.6):** 4-Good. The angle of the eastern bank is 15^{o} and the western bank angle 30^{o}.
3. **Bank Cutting (.4):** 2-Excellent.
4. **Vegetative Bank Protection (.8):** 3-Excellent.
5. **Mass Wasting or Bank Failure (.8):** 3-Excellent. No apparent mass wasting events.
6. **Bar Development (.6):** 4-Good.
7. **Debris-Jam Potential (.2):** 1-Excellent. Minimal debris close to banks.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 1-Excellent. None observed. Water moves freely through wide and open channel, though slowly.
9. **Channel-bed Material Consolidation and Armoring (.8):** 4-Good.

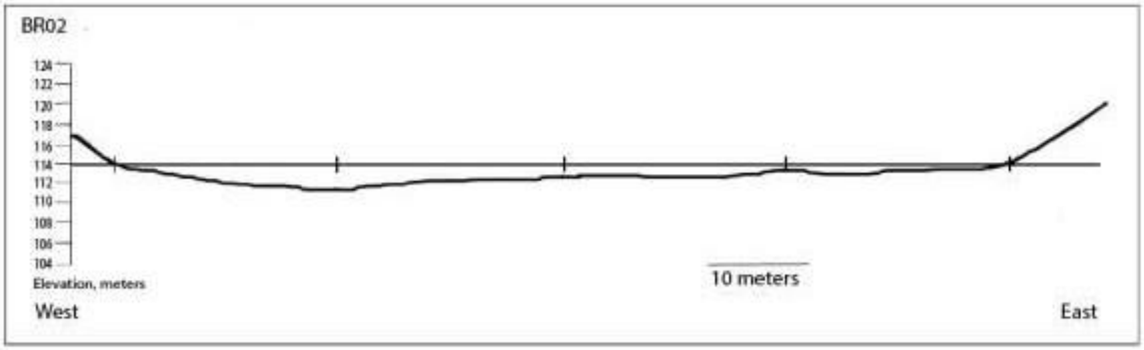
   Total: 4(.6) + 4(.6) + 2(.4) + 3(.8) + 3(.8) + 4(.6) + 1(.2) + 1(.2) + 4(.8) = 16.4

Figure 95: Eastern bank at BR01. Notice minimal debris and vegetation reaching waterline.

Figure 96: View of western bank of BR01 from eastern bank. Notice wide channel, free of flow obstructions.

BR02:

BR02 was located approximately 500 meters south of Buster Chatham Rd., just upstream of a sharp bend to the east. An extensive bar was forming at BR02, requiring portage across parts of the channel on foot. A cross section is presented below.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3-Excellent.

2. Average Bank Angle (.6): 6-Good. The eastern bank angle was 23° and the western bank angle 36°.

3. Bank Cutting (.4): 2-Excellent.

4. Vegetative Bank Protection (.8): 4-Good. Vegetation is abundant, but mostly grassy

5. Mass Wasting or Bank Failure (.8): 7-Fair. Minor slump present.

6. Bar Development (.6): 8-Fair. Wide bar, sparsely vegetated

7. Debris-Jam Potential (.2): 8-Fair. Significant debris.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 8-Fair.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

$3(.6) + 6(.6) + 2(.4) + 4(.8) + 7(.8) + 8(.6) + 8(.2) + 8(.2) + 3(.8) = 25.4$

Figure 97: Debris at BR02

Figure 98: Bar forming at BR02

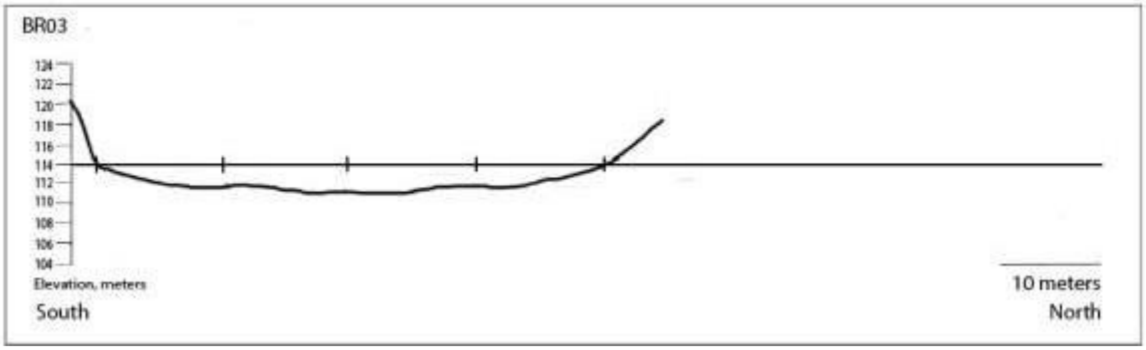
Figure 101: Slump on western bank of BR02

Figure 102: Abundant, grassy vegetation

BR03:

BR03 was located immediately downstream of a sharp eastward turn of the river channel.

A cross section is presented below.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 4-Good.

2. Average Bank Angle (.6): 9-Fair. The angle of the northern bank measured 45° and the southern bank angle 72°.

3. Bank Cutting (.4): 2-Excellent.

4. Vegetative Bank Protection (.8): 3-Excellent. Vegetation is dense, extending to or near the water.

5. Mass Wasting or Bank Failure (.8): 3-Excellent.

6. Bar Development (.6): 6-Good.

7. Debris-Jam Potential (.2): 2-Excellent. Debris near banks.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent. None observed. Water moves freely through wide and open channel, though slowly.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

4(.6) + 9(.6) + 2(.4) + 3(.8) + 3(.8) + 6(.6) + 2(.2) + 1(.2) + 3(.8) = 20

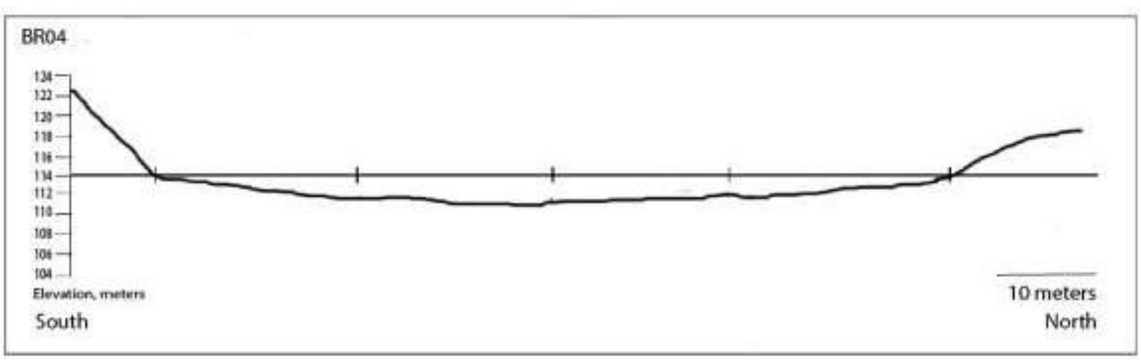
Figure 103: Typical bank vegetation at BR03

Figure 104: View across river at BR03. Notice clear channel and thick vegetation, with some root exposure.

Figure 105: Most vegetation at this location is vertical, with one notable exception. Note that some channel stabilization has been utilized along this stretch.

Location 4 (BR04):

BR04 was located approximately 350 meters downstream from BR03, in a stretch that is beginning to exhibit occasional channel stabilization where the channel is directly in front of residences.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 5- Good.

2. Average Bank Angle (.6): 7-Fair. The bank angle of the southern bank is 45^{o} and the northern bank angle 29^{o}.

3. Bank Cutting (.4): 4-Good.

4. Vegetative Bank Protection (.8): 3-Excellent.

5. Mass Wasting or Bank Failure (.8): 6-Good. Very slight earthflow.

6. Bar Development (.6): 6-Good.

7. Debris-Jam Potential (.2): 3-Excellent. Some debris present near banks.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent. None observed. Water moves freely through wide and open channel, though slowly.

9. Channel-bed Material Consolidation and Armoring (.8): 4-Good.

5(.6) + 7(.6) + 4(.4) + 3(.8) + 6(.8) + 6(.6) + 3(.2) + 1(.2) + 4(.8) = 23.6

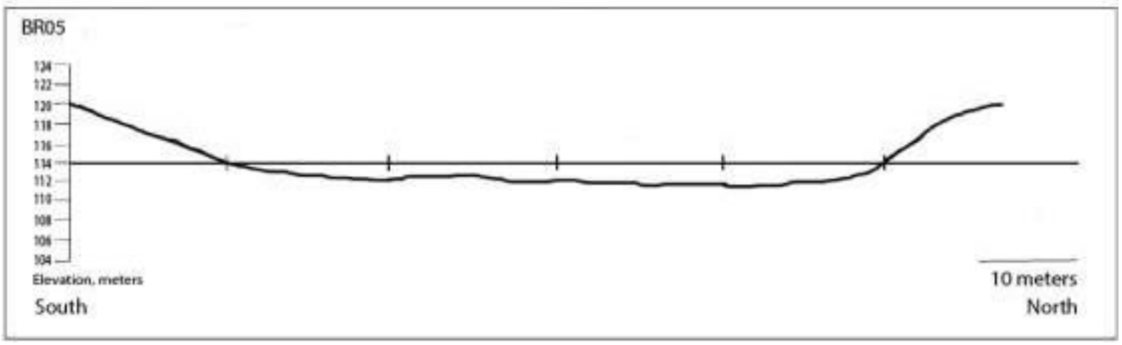
Figure 107: Slight earthflow at BR04

Figure 106: Bank at BR04, with more frequent leaning vegetation

Figure 108: View of bank at BR04. As this location is near a residential area, some channel stabilization is utilized. Notice the leaning vegetation and minor debris.

BR05:

BR05 is located approximately one kilometer downstream from BR04 and one kilometer upstream from a southeastern turn of the river channel.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 6- Good.

2. Average Bank Angle (.6): 5-Good. The southern bank angle was 19^o and the northern bank angle 35^o.

3. Bank Cutting (.4): 7-Fair.

4. Vegetative Bank Protection (.8): 6-Good.

5. Mass Wasting or Bank Failure (.8): 3-Excellent. No apparent mass wasting events.

6. Bar Development (.6): 5-Good.

7. Debris-Jam Potential (.2): 1-Excellent. No debris present in channel or near banks.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent. None observed. Water moves freely through wide and open channel, though slowly.

9. Channel-bed Material Consolidation and Armoring (.8): 6-Good.

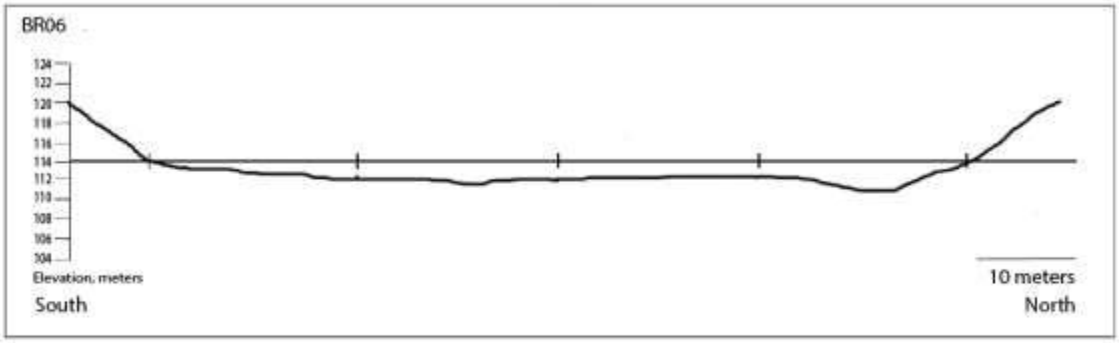
$$6(.6) + 5(.6) + 7(.4) + 6(.8) + 3(.8) + 5(.6) + 1(.2) + 1(.2) + 6(.8) = 24.8$$

Figure 109: Typical bank at BR05

Figure 110: Vegetation reaching to water, though mostly grassy

BR06:

BR06 is located approximately 750 meters downstream from Location BR05 and just upstream of a southeastern turn of the river channel.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 7- Fair.

2. Average Bank Angle (.6): 7-Fair. The southern bank has an angle of 35^{o} and the northern bank has an angle of 37^{o}.

3. Bank Cutting (.4): 2-Excellent. Very little to none on southern bank. Northern bank is well protected, but has occasional instances of cutting.

4. Vegetative Bank Protection (.8): 4-Good. Southern bank is very well vegetated. The northern bank has extensive landscaping.

5. Mass Wasting or Bank Failure (.8): 3-Excellent. No apparent mass wasting events.

6. Bar Development (.6): 3-Excellent. Bars are fully vegetated. Most sediment is fine clay.

7. Debris-Jam Potential (.2): 1-Excellent. No debris present in channel or near banks.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent. None observed. Water moves freely through wide and open channel, though slowly.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent. Most material is <4mm, but this is typical of the area. Material is well consolidated, particularly where limestone bedrock is present.

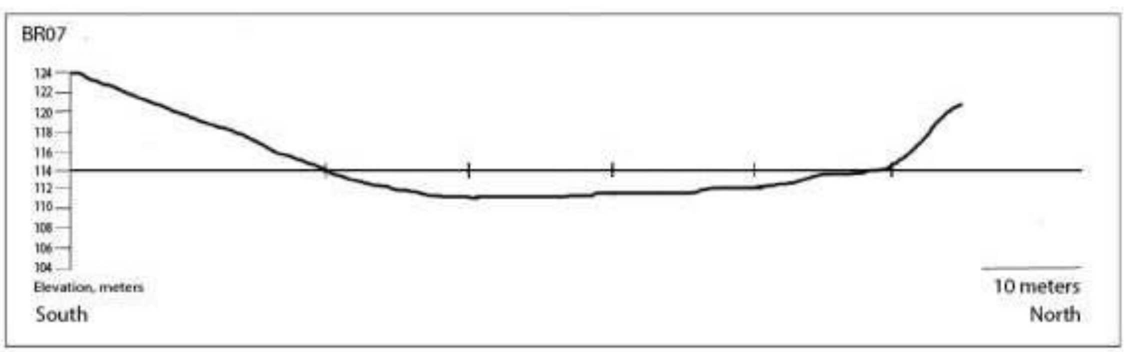
7(.6) + 7(.6) + 2(.4) + 4(.8) + 3(.8) + 3(.6) + 1(.2) + 1(.2) + 3(.8) = 19.4

Figure 111: Very well vegetated southern bank at BR06.

Figure 112: Northern bank at BR06 has been impacted by suburbanization. Most banks are well maintained, with occasional cuts like the one above.

BR07:

BR07 is located immediately downstream of a southeastern turn of the river channel.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 5- Good.

2. Average Bank Angle (.6): 7-Fair. The bank angle of the southern bank on this section measured 15^o and the northern bank angle was 50^o.

3. Bank Cutting (.4): 6-Good.

4. Vegetative Bank Protection (.8): 6-Good. Infrequent raw banks above 30 cm.

5. Mass Wasting or Bank Failure (.8): 5-Good.

6. Bar Development (.6): 5-Good.

7. Debris-Jam Potential (.2): 1-Excellent. No debris present in channel or near banks.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent. None observed. Water moves freely through wide and open channel, though slowly.

9. Channel-bed Material Consolidation and Armoring (.8): 6-Good.

5(.6) + 7(.6) + 6(.4) + 6(.8) + 5(.8) + 5(.6) + 1(.2) + 1(.2) + 6(.8) = 26.6

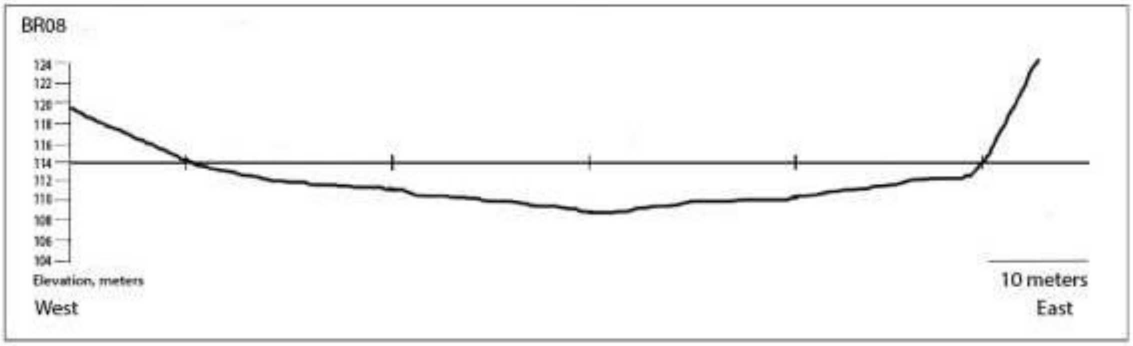
Figure 114: Typically, vegetation at BR07 was very thick and extended to the water line.

Figure 113: Occasional cutting was present, some severe.

Figure 115: One of the more severe cuts at BR07.

BR08:

BR08 is located approximately 400 meters upstream of FM 3051/Lakeshore Dr.



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 5- Good. Banks consisted of bedded limestone and limestone clay.

2. **Average Bank Angle (.6):** 7-Fair. The bank angle of the eastern bank measured 61° and the western bank angle was 25°.

3. **Bank Cutting (.4):** 5-Good.

4. **Vegetative Bank Protection (.8):** 6-Good.

5. **Mass Wasting or Bank Failure (.8):** 3-Excellent.

6. **Bar Development (.6):** 3-Excellent.

7. **Debris-Jam Potential (.2):** 1-Excellent. No debris present in channel or near banks.

8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 1-Excellent. None observed. Water moves freely through wide and open channel, though slowly.

9. **Channel-bed Material Consolidation and Armoring (.8):** 3-Excellent.

5(.6) + 7(.6) + 5(.4) + 6(.8) + 3(.8) + 3(.6) + 1(.2) + 1(.2) + 3(.8) = 21

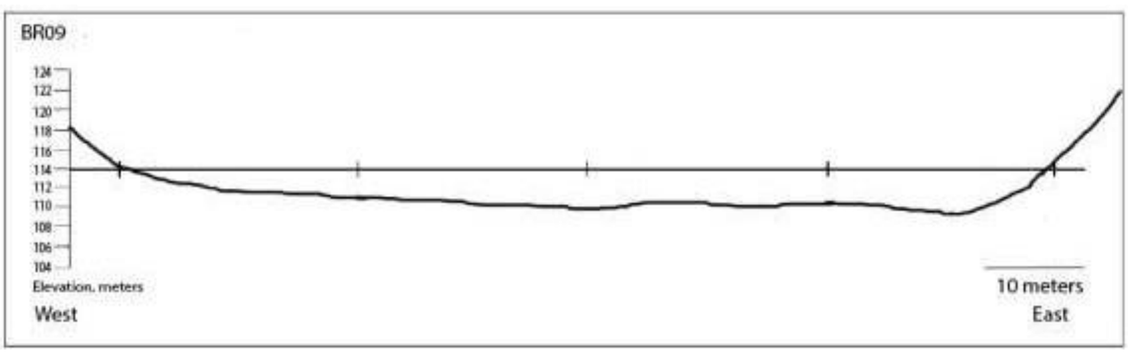
Figure 116: Bedded limestone on eastern bank.

Figure 117: Well-vegetated western bank

Figure 118: Clear channel and vertical vegetation

BR09:

BR09 is located at FM 3051/Lakeshore Dr.



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 5- Good. Banks consisted of bedded limestone and limestone clay.

2. **Average Bank Angle (.6):** 7-Fair. The bank angle of the eastern bank measured 42° and the western bank angle was 39°.

3. **Bank Cutting (.4):** 5-Good. Infrequent noticeable cuts.

4. **Vegetative Bank Protection (.8):** 5-Good.

5. **Mass Wasting or Bank Failure (.8):** 3-Excellent.

6. **Bar Development (.6):** 3-Excellent.

7. **Debris-Jam Potential (.2):** 1-Excellent. No debris present in channel or near banks.

8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 1-Excellent. None observed. Water moves freely through wide and open channel, though slowly.

9. **Channel-bed Material Consolidation and Armoring (.8):** 3-Excellent.

5(.6) + 7(.6) + 5(.4) + 5(.8) + 3(.8) + 3(.6) + 1(.2) + 1(.2) + 3(.8) = 20.2

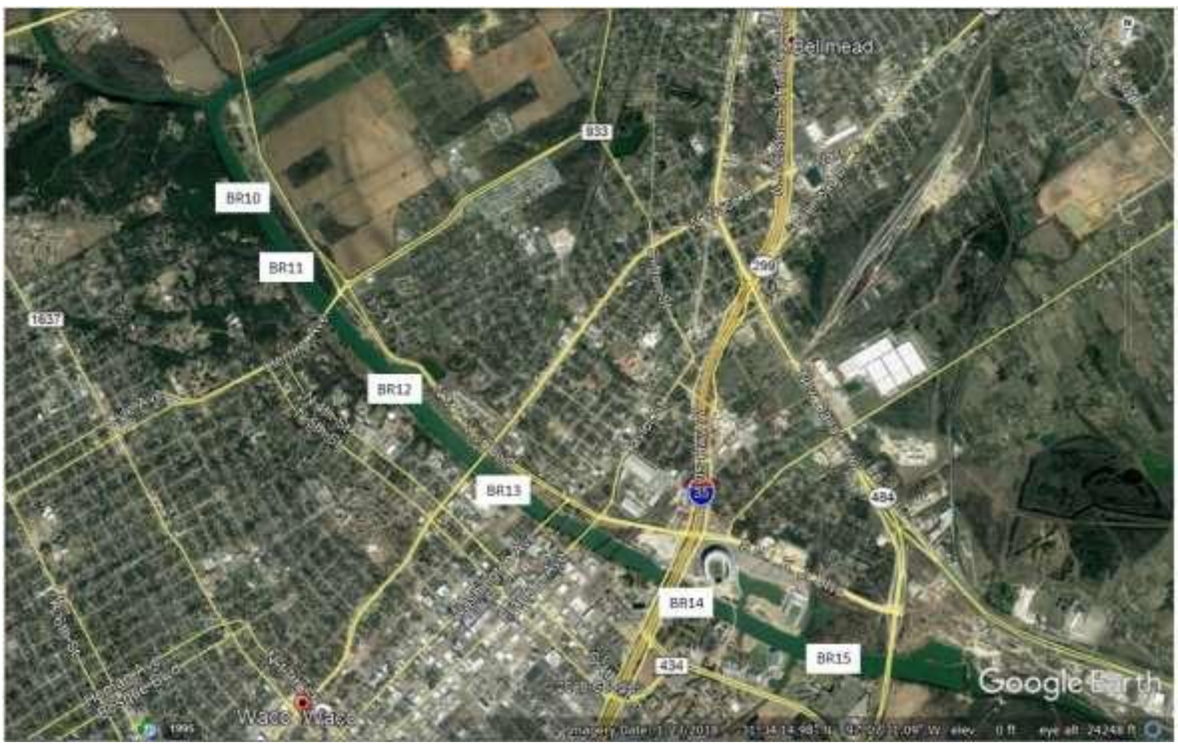
Figure 119: Increased erosion observed near the FM 3051 overpass

Figure 121: Dense vegetation at BR09

Figure 120: Cutting at BR09

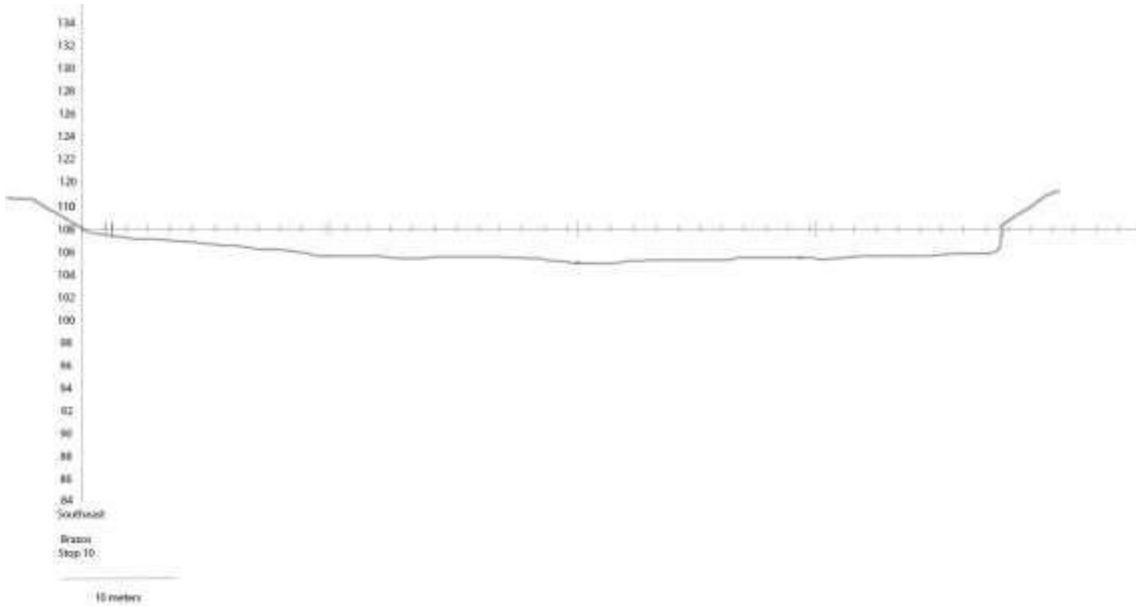
The Brazos River, Urban

A 3.5-mile stretch of the Brazos River as is passes through Waco, Texas, was studied. This reach begins at Brazos Park East off of North M.L.K. Blvd. upstream of Waco and ends at the Baylor Ballpark (baseball field) downstream of the city. Six locations were studied on this reach.



BR10:

BR10 is located at the southeastern edge of Brazos Park East.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 4-Good. The bank angle of the eastern bank measured 11° and the western bank angle was 60°.

3. Bank Cutting (.4): 2-Excellent.

4. Vegetative Bank Protection (.8): 3-Excellent.

5. Mass Wasting or Bank Failure (.8): 3-Excellent.

6. Bar Development (.6): 4-Good.

7. Debris-Jam Potential (.2): 4-Good. Small amounts of debris near banks.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 2-Excellent. None observed.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

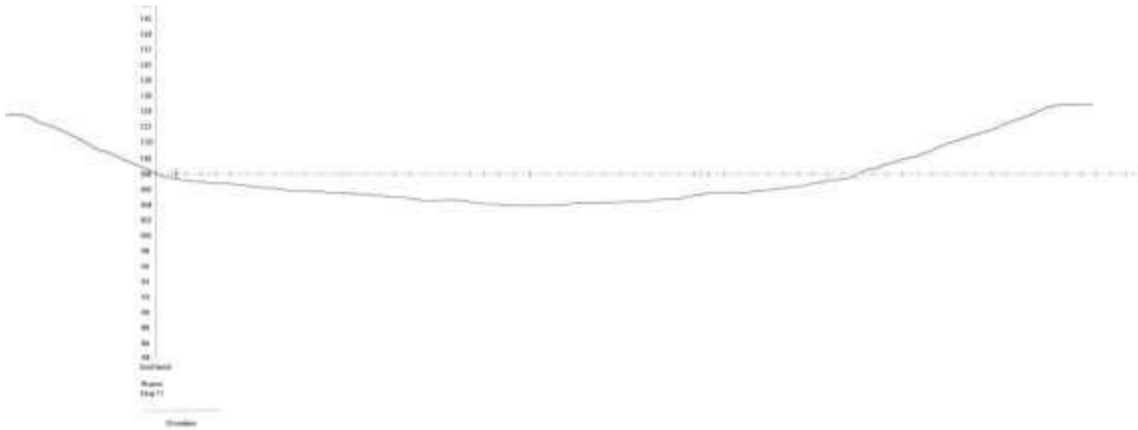
Total: 3(.6) + 4(.6) + 2(.4) + 3(.8) + 3(.8) + 4(.6) + 4(.2) + 2(.2) + 3(.8) = 15.8

Figure 122: Well-vegetated northern bank of the Brazos River at BR10. Notice the limestone cliffs on the southern bank.

Figure 123: Southern bank of Brazos River at BR10.

BR11:

BR11 is located approximately 400 meters upstream of the Herring Ave. overpass.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 8-Fair. The bank angle of the eastern bank measured 35º and the western bank angle was 57º.

3. Bank Cutting (.4): 4-Good. Some raw banks present.

4. Vegetative Bank Protection (.8): 4-Good.

5. Mass Wasting or Bank Failure (.8): 3-Excellent.

6. Bar Development (.6): 4-Good.

7. Debris-Jam Potential (.2): 3-Excellent.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent. None observed.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 3(.6) + 8(.6) + 4(.4) + 4(.8) + 3(.8) + 4(.6) + 3(.2) + 1(.2) + 3(.8) = 19.4

Figure 124: Well-vegetated northern bank at B11, though some trees are leaning.

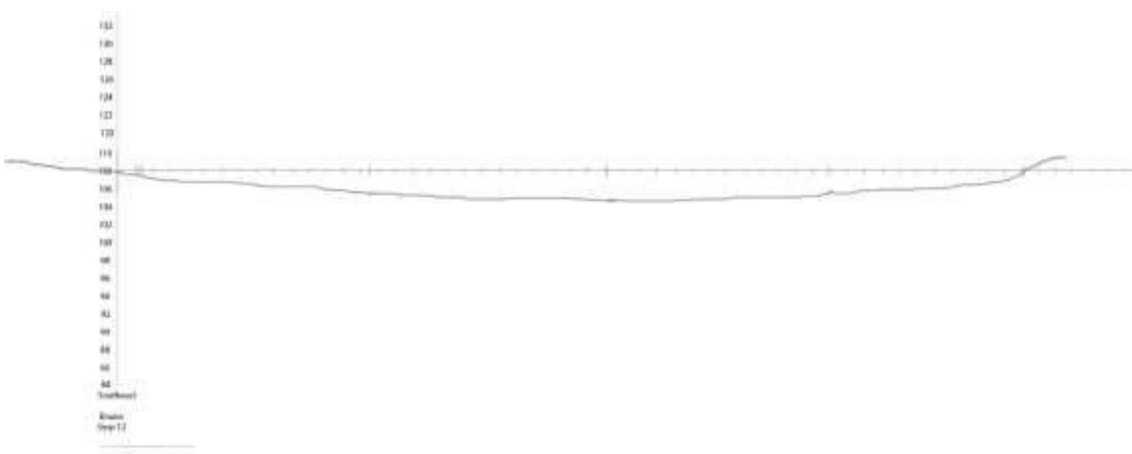
Figure 125: The southern bank at BR11, upstream of urban influence.

Figure 126: Nearer the city, the southern bank had experienced landscape modification.

Figure 127: Occasional mass wasting on the landscaped portion.

BR12:

BR12 is located halfway between Herring Ave. and E. Waco Dr.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 7-Fair. The bank angle of the northern bank measured 20^{o} and the southern bank angle was 37^{o}.

3. Bank Cutting (.4): 4-Good.

4. Vegetative Bank Protection (.8): 6-Good.

5. Mass Wasting or Bank Failure (.8): 6-Good.

6. Bar Development (.6): 4-Good.

7. Debris-Jam Potential (.2): 3-Excellent.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 3(.6) + 7(.6) + 4(.4) + 6(.8) + 6(.8) + 4(.6) + 3(.2) + 1(.2) + 3(.8) = 22.8

Figure 128: Southern bank at BR12

Figure 129: Localized bank instability is seen immediately adjacent to engineering structures.

Figure 130: Northern bank at BR12

BR13:

BR13 is halfway between E. Waco Dr. and Washington Ave.

Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 7-Fair. The northern bank angle was inaccessible, as it was covered in poison ivy. The southern bank angle was 40^o.

3. Bank Cutting (.4): 3-Excellent.

4. Vegetative Bank Protection (.8): 3-Excellent.

5. Mass Wasting or Bank Failure (.8): 4-Good.

6. Bar Development (.6): 4-Good.

7. Debris-Jam Potential (.2): 1-Excellent.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 3(.6) + 7(.6) + 3(.4) + 3(.8) + 4(.8) + 4(.6) + 1(.2) + 1(.2) + 3(.8) = 18

Figure 131: Example of channel modification at BR13

Figure 132: Northern bank was modified, but retained much of its native vegetation.

Figure 133: Some regions on this reach retained extensive native vegetation.

Figure 134: Natural vegetation alternated with extensive clearing and modification. BR14 is located directly in front of the McLane Football Stadium. This portion is extensively modified.

Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 4-Good. The northern bank angle is 30^{o}. The southern bank angle was 10^{o}. The southern bank angle measurement was taken from a natural segment of the bank, but most of the southern bank has been steepened and flattened at the top.

3. Bank Cutting (.4): 4-Good. The banks are landscaped and reinforced with concrete.

4. Vegetative Bank Protection (.8): 7-Fair.

5. Mass Wasting or Bank Failure (.8): 5-Good.

6. Bar Development (.6): 4-Good.

7. Debris-Jam Potential (.2): 1-Excellent.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 3(.6) + 4(.6) + 4(.4) + 7(.8) + 5(.8) + 4(.6) + 1(.2) + 1(.2) + 3(.8) = 20.6

Figure 135: Extensively modified northern bank at BR14.

Figure 136: Modified northern bank, supporting football stadium of Baylor University.

Figure 137: Open channel with no debris, extensive modification.

Figure 138: Vegetation on southern bank was healthy, though some trees were leaning.

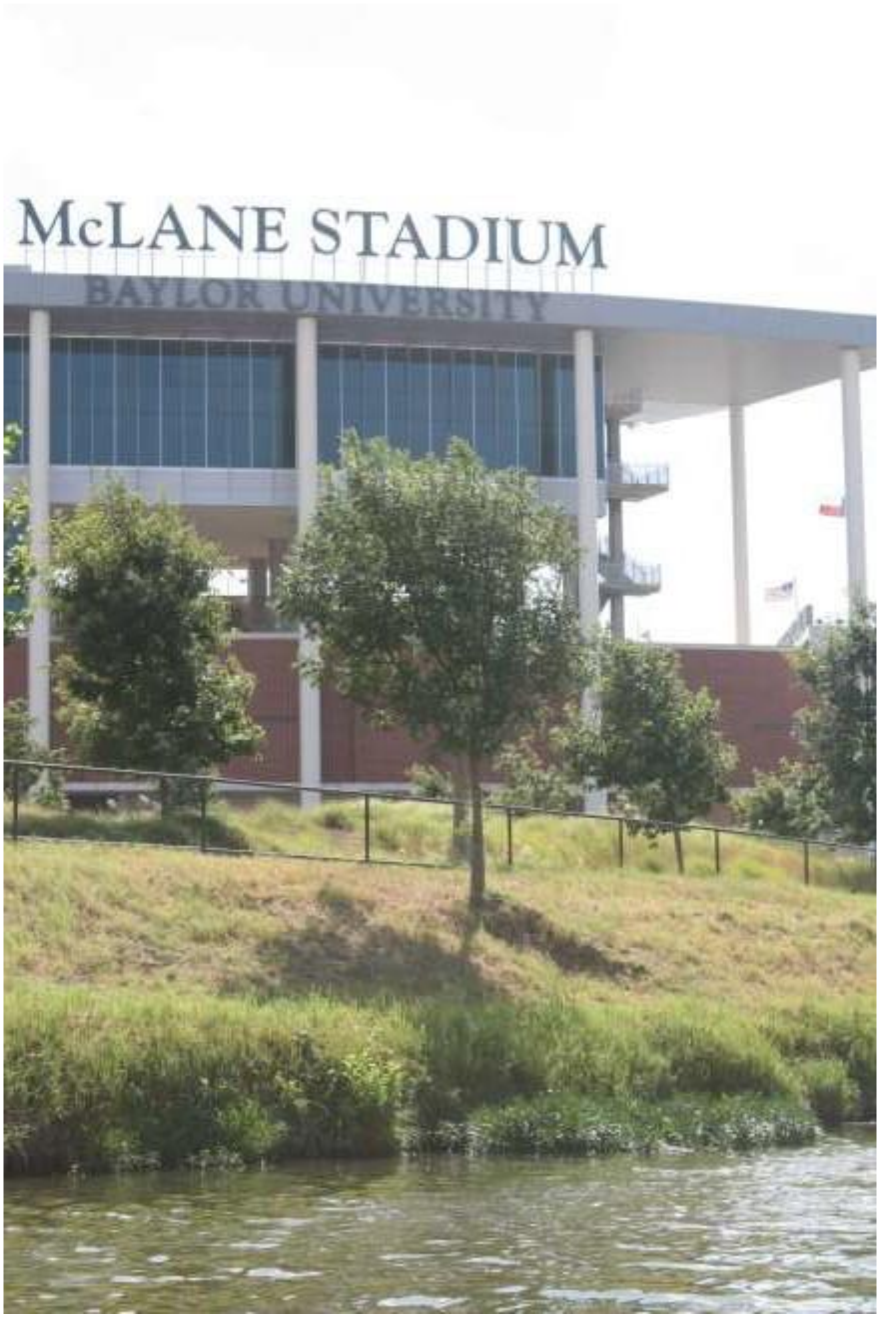


Figure 139: Grassy northern bank in front of McLane Stadium on northern bank.

Figure 140: This reach had increased cutting along some of the modified areas.

Figure 141:Close-up of undercutting

BR15 is located in front of the Baylor Ballpark (on southern bank). The southern bank is highly modified, but the northern bank retains a natural condition.

Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 6-Good. The northern bank angle is 24^o. The southern bank angle was 40^o.

3. Bank Cutting (.4): 3-Excellent. Northern bank is at 2 and southern bank at 4.

4. Vegetative Bank Protection (.8): 3-Excellent. Northern bank is 2 and southern bank is 4.

5. Mass Wasting or Bank Failure (.8): 1-Excellent.

6. Bar Development (.6): 4-Good.

7. Debris-Jam Potential (.2): 1-Excellent.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1-Excellent.

9. Channel-bed Material Consolidation and Armoring (.8): 2-Excellent.

Total: 3(.6) + 6(.6) + 3(.4) + 3(.8) + 1(.8) + 4(.6) + 1(.2) + 1(.2) + 2(.8) = 14.2

Figure 142: On southern bank, bank erosion is extensive.

Figure 143: Fence failure resulting from bank slump

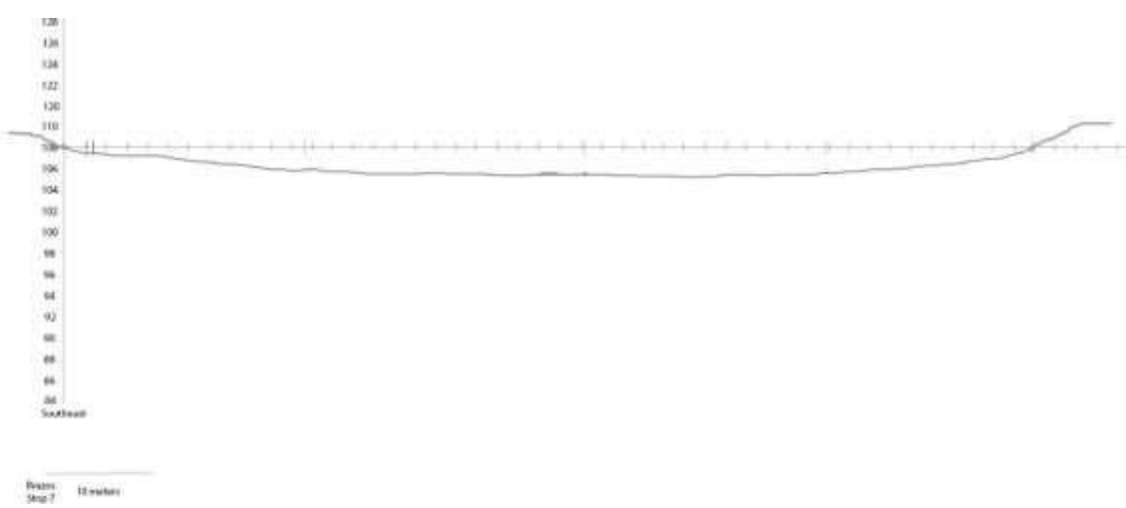
Figure 144: Natural vegetation on northern bank.

Brazos River, Downstream of Waco

A 4.5 mile reach of the Brazos River downstream of Waco was studied, beginning at the TX-6 overpass.

BR16:

BR16 is located at the Texas-6/Loop 340 overpass.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 7- Fair. Sediment is very sandy.

2. Average Bank Angle (.6): 3-Excellent. The bank angle of the eastern bank measured 25^o and the western bank angle was 15^o.

3. Bank Cutting (.4): 3-Excellent.

4. Vegetative Bank Protection (.8): 2-Excellent.

5. Mass Wasting or Bank Failure (.8): 1-Excellent.

6. Bar Development (.6): 5-Good. Vegetation has been largely trampled by humans.

7. Debris-Jam Potential (.2): 4-Good. Small amounts of debris near banks.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 4-Good.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 7(.6) + 3(.6) + 3(.4) + 2(.8) + 1(.8) + 5(.6) + 4(.2) + 4(.2) + 3(.8) = 16.6

Figure 145: TX-6 overpass, some anthropogenic debris

Figure 146: Vegetation here is dense, diverse, and mostly vertical.

Figure 147: Close-up of northern bank

BR17:

BR17 is located approximately 800 meters downstream of the Texas-6/Loop 340 overpass.

Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 4- Good.

2. Average Bank Angle (.6): 7-Fair. The bank angle of the eastern bank measured 30^o and the western bank angle was 45^o.

3. Bank Cutting (.4): 7-Fair.

4. Vegetative Bank Protection (.8): 7-Fair.

5. Mass Wasting or Bank Failure (.8): 3-Excellent.

6. Bar Development (.6): 3-Excellent.

7. Debris-Jam Potential (.2): 5-Good. Small amounts of debris near banks.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 4-Good.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 4(.6) + 7(.6) + 7(.4) + 7(.8) + 3(.8) + 3(.6) + 5(.2) + 4(.2) + 3(.8) = 23.4

Figure 148: Leaning vegetation at BR17.

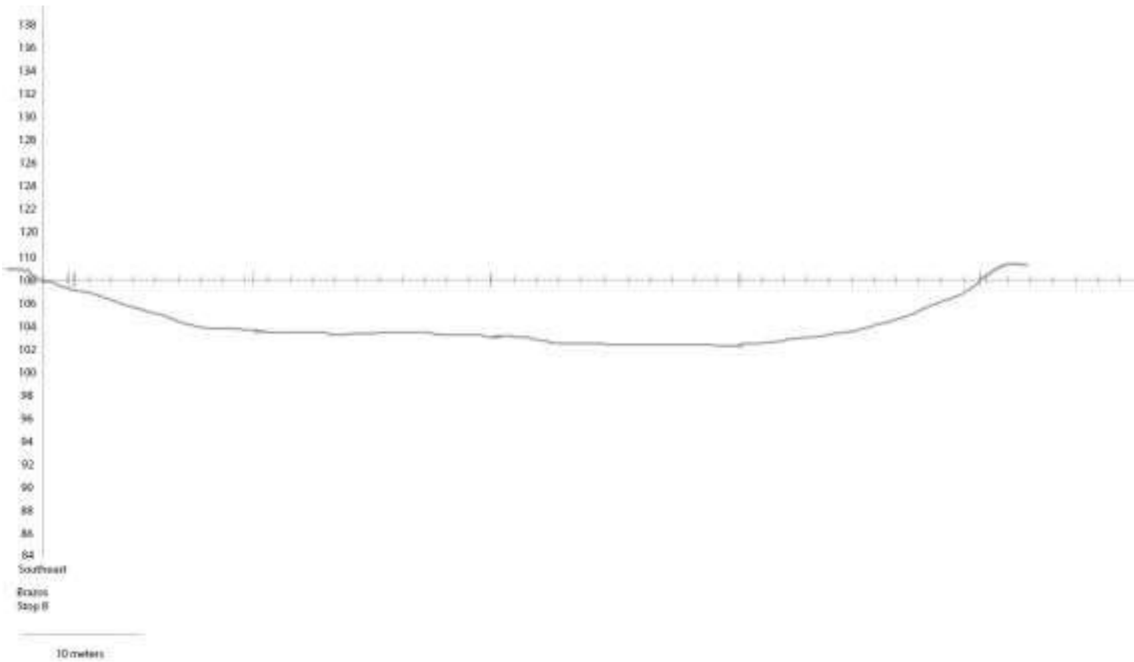
Figure 149: Bank cutting and exposed roots at BR17.

Figure 150: Exposed root mats at BR17.

Figure 151: Small earthflow

BR18:

BR18 is located just upstream of an eastward bend in the river channel. Sand bars are extensive here.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 4- Good.

2. Average Bank Angle (.6): 6-Good. The bank angle of the eastern bank measured 20º and the western bank angle was 35º.

3. Bank Cutting (.4): 7-Fair.

4. Vegetative Bank Protection (.8): 6-Good.

5. Mass Wasting or Bank Failure (.8): 4-Good.

6. Bar Development (.6): 10-Poor.

7. Debris-Jam Potential (.2): 6-Good.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 6-Good.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 4(.6) + 6(.6) + 7(.4) + 6(.8) + 4(.8) + 10(.6) + 6(.2) + 6(.2) + 3(.8) = 27.6

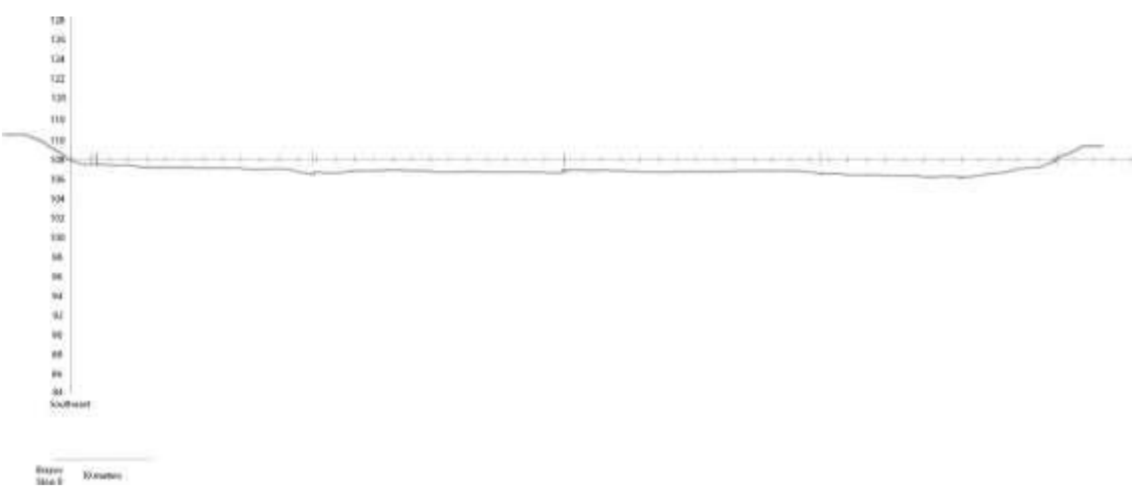
Figure 152: Continuous bank cutting and exposed roots at BR18

Figure 153: A wide, coarse-grained bar consumed much of the river channel here.

Figure 154: The western bank experiences increased erosion as it grades to a cutbank.

Figure 155: Lush vegetation on eastern bank
BR19:

BR19 is located on a straight reach between an eastward turn and southward turn in the river.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 4- Good.

2. Average Bank Angle (.6): 6-Good. The bank angle of the northern bank measured 55º and the southern bank angle was 36º.

3. Bank Cutting (.4): 7-Fair.

4. Vegetative Bank Protection (.8): 6-Good.

5. Mass Wasting or Bank Failure (.8): 4-Good.

6. Bar Development (.6): 4-Good.

7. Debris-Jam Potential (.2): 3-Excellent.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 3-Excellent.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 4(.6) + 6(.6) + 7(.4) + 6(.8) + 4(.8) + 4(.6) + 3(.2) + 3(.2) + 3(.8) = 22.8

Figure 156: Vegetation is dense at BR19, though bank cutting is visible beneath branches

Figure 157: Close-up of bank cutting

Figure 158: Coarse-grained bar continued to BR19.

BR20:

BR20 is located just downstream of a southward bend in the river channel, just upstream of the confluence of a small creek.

Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 8-Fair. The bank angle of the northeastern bank measured 47^{o} and the southwestern bank angle was 19^{o}.

3. Bank Cutting (.4): 9-Fair.

4. Vegetative Bank Protection (.8): 8-Fair.

5. Mass Wasting or Bank Failure (.8): 8-Fair.

6. Bar Development (.6): 6-Good.

7. Debris-Jam Potential (.2): 5-Good.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 5-Good.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 3(.6) + 8(.6) + 9(.4) + 8(.8) + 8(.8) + 6(.6) + 5(.2) + 5(.2) + 3(.8) = 31

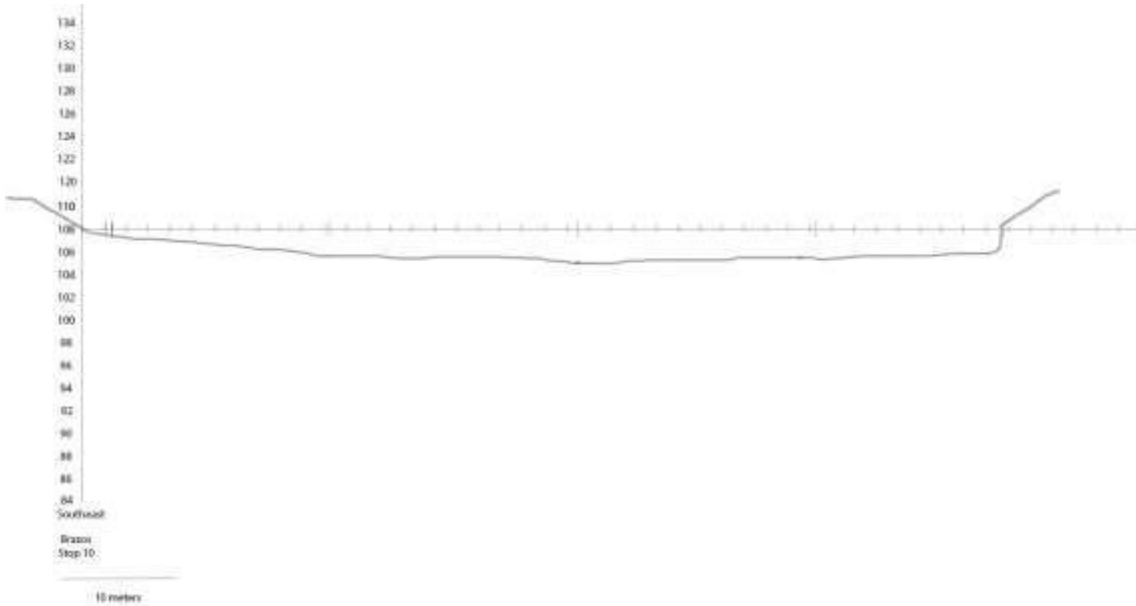
Figure 159: Bank cutting and erosion was extensive at BR20.

Figure 160: Continuous cuts at BR20

Figure 161: Vegetation is dense at BR20, though cuts are visible beneath foliage.

BR21:

BR21 is located just downstream the confluence of a small creek.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 7-Fair. The bank angle of the eastern bank measured 28º and the western bank angle was 30º.

3. Bank Cutting (.4): 8-Fair.

4. Vegetative Bank Protection (.8): 7-Fair.

5. Mass Wasting or Bank Failure (.8): 6-Good.

6. Bar Development (.6): 6-Good.

7. Debris-Jam Potential (.2): 5-Good.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 4-Good.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 3(.6) + 7(.6) + 8(.4) + 7(.8) + 6(.8) + 6(.6) + 5(.2) + 4(.2) + 3(.8) = 27.4

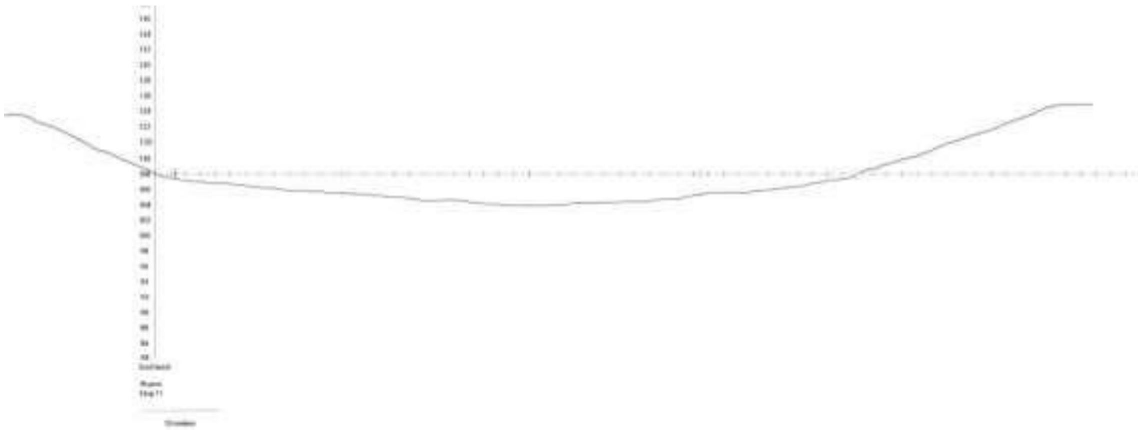
Figure 162: Exposed roots at BR21

Figure 163: Leaning tree at BR21

Figure 164: BR21 had lush vegetation which was adjusting as the underlying bank eroded.

BR22:

BR22 is located about 500 meters downstream of BR21.



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 4- Excellent.

2. Average Bank Angle (.6): 8-Fair. The bank angle of the eastern bank measured 42º and the western bank angle was 46º.

3. Bank Cutting (.4): 9-Fair.

4. Vegetative Bank Protection (.8): 8-Fair.

5. Mass Wasting or Bank Failure (.8): 5-Good.

6. Bar Development (.6): 6-Good. Highly vegetated, but fine grained bars.

7. Debris-Jam Potential (.2): 4-Good.

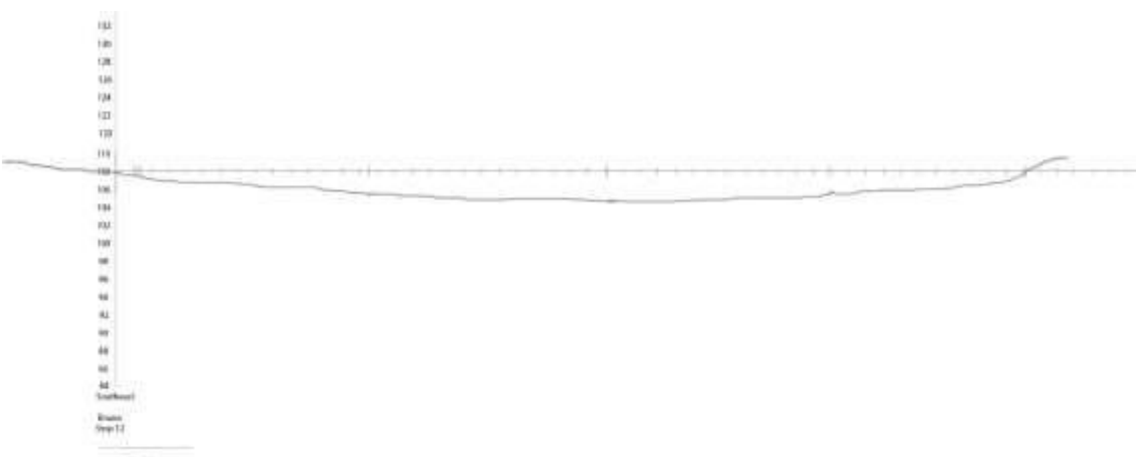
8. Obstructions, Flow Deflectors, Sediment Traps (.2): 4-Good.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 4(.6) + 8(.6) + 9(.4) + 8(.8) + 5(.8) + 6(.6) + 4(.2) + 4(.2) + 3(.8) = 28.8

Figure 165: Leaning vegetation at BR22

BR23:



BR23 is located about 750 meters downstream of BR22, just after a slight westward bend in the river.

Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 9-Fair. The bank angle of the eastern bank measured 59° and the western bank angle was 42°.

3. Bank Cutting (.4): 5-Good.

4. Vegetative Bank Protection (.8): 6-Good.

5. Mass Wasting or Bank Failure (.8): 4-Good.

6. Bar Development (.6): 6-Good.

7. Debris-Jam Potential (.2): 3-Excellent.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 3-Excellent.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 3(.6) + 9(.6) + 5(.4) + 6(.8) + 4(.8) + 6(.6) + 3(.2) + 3(.2) + 3(.8) = 24.4

Figure 166: Dense vegetation at BR23, less bank cutting

Figure 167: One of occasional bank failures at BR23

BR24:

BR24 is located about 700 meters downstream of BR23, on a reach experiencing modification by residential impact.

Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 2- Excellent.

2. Average Bank Angle (.6): 7-Fair. The bank angle of the eastern bank measured 23^o and the western bank angle was 56^o.

3. Bank Cutting (.4): 9-Fair.

4. Vegetative Bank Protection (.8): 7-Fair.

5. Mass Wasting or Bank Failure (.8): 7-Fair.

6. Bar Development (.6): 6-Good.

7. Debris-Jam Potential (.2): 5-Good.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 5-Good.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 2(.6) + 7(.6) + 9(.4) + 7(.8) + 7(.8) + 6(.6) + 5(.2) + 5(.2) + 3(.8) = 28.2

Figure 168: Residential modification less regulated than in the city limits was apparent at BR24.

Figure 169: Note that the dock on the right is leaning into the river channel.

Figure 170: Even where natural vegetation remained, bank failure was extensive at BR24.

BR25:

BR25 is located about 550 meters downstream of BR24, just upstream of a slight eastward bend in the river.

Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3- Excellent.

2. Average Bank Angle (.6): 6-Good. The bank angle of the eastern bank measured 25º and the western bank angle was 45º.

3. Bank Cutting (.4): 5-Good.

4. Vegetative Bank Protection (.8): 6-Good.

5. Mass Wasting or Bank Failure (.8): 4-Good.

6. Bar Development (.6): 4-Good.

7. Debris-Jam Potential (.2): 3-Excellent.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 3-Excellent.

9. Channel-bed Material Consolidation and Armoring (.8): 3-Excellent.

Total: 3(.6) + 6(.6) + 5(.4) + 6(.8) + 4(.8) + 4(.6) + 3(.2) + 3(.2) + 3(.8) = 21.4

Figure 171: Homemade river modification continued at BR25.

Figure 172: Modification typically included vegetation removal, structures built close to the river channel, and little or no stabilization.

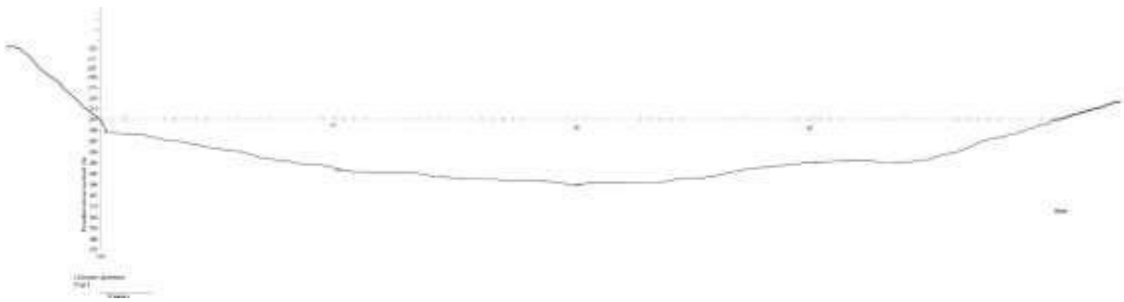
Figure 173: Where left natural, vegetation was thick and grassy

APPENDIX C

ASSESSMENTS OF CHANNEL STABILITY USING MORPHOLOGICAL INDICATORS: COLORADO RIVER NEAR AUSTIN, TEXAS

The Colorado River was studied upstream of Austin, Texas. Put-in was at Shaffer Bend Recreation Area, 55 miles northwest of Austin and managed by the Lower Colorado River Authority (LCRA). Take-out was 5.6 miles downstream at Grelle Recreation Area, also managed by the LCRA. In this region, the river flows through a slightly modified or natural channel. Prior urbanization exposure is slight, as at this point the Colorado River has flowed through no cities larger than Marble Falls, Texas (population 6,514).

CR01:



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 1- Solid bedrock.

2. Average Bank Angle (.6): 1- Vertical, but not sediment; limestone bluffs

3. Bank Cutting (.4): NA

4. Vegetative Bank Protection (.8): NA

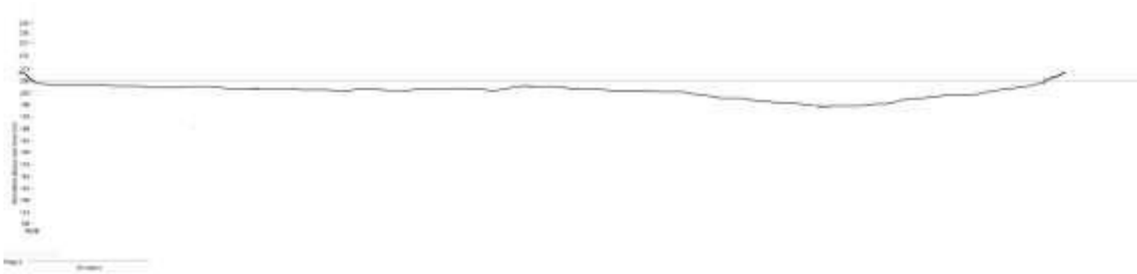
5. Mass Wasting or Bank Failure (.8):1

6. Bar Development (.6): 1

7. Debris-Jam Potential (.2): 1.

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 3

CR02:



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 4.

2. **Average Bank Angle (.6):** 6

3. **Bank Cutting (.4):** 10

4. **Vegetative Bank Protection (.8):** 10

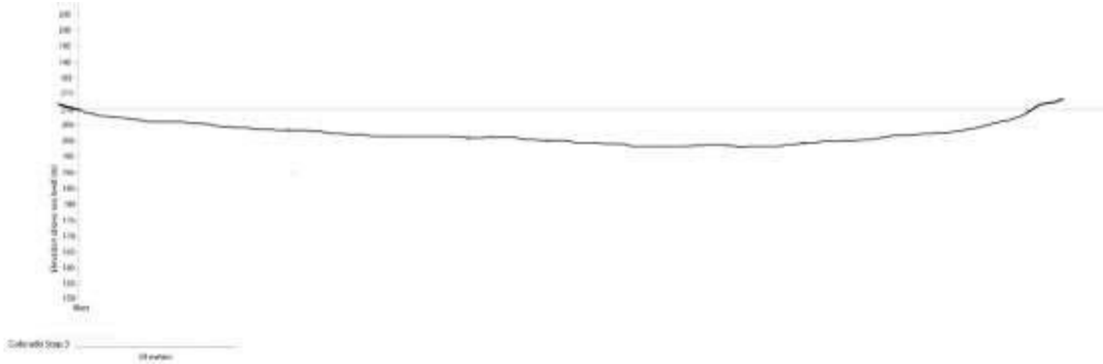
5. **Mass Wasting or Bank Failure (.8):7**

6. **Bar Development (.6): 1**

7. **Debris-Jam Potential (.2): 1**.

8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 3**

CR03:



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 8

2. **Average Bank Angle (.6):** 9

3. **Bank Cutting (.4): 4**

4. **Vegetative Bank Protection (.8):** 6

5. **Mass Wasting or Bank Failure (.8):3**

6. **Bar Development (.6): 1**

7. **Debris-Jam Potential (.2): 1**.

8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 7**

CR04:

Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 7

2. Average Bank Angle (.6): 2

3. Bank Cutting (.4): 1

4. Vegetative Bank Protection (.8): 4

5. Mass Wasting or Bank Failure (.8):1

6. Bar Development (.6): 1

7. Debris-Jam Potential (.2): 2

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 2

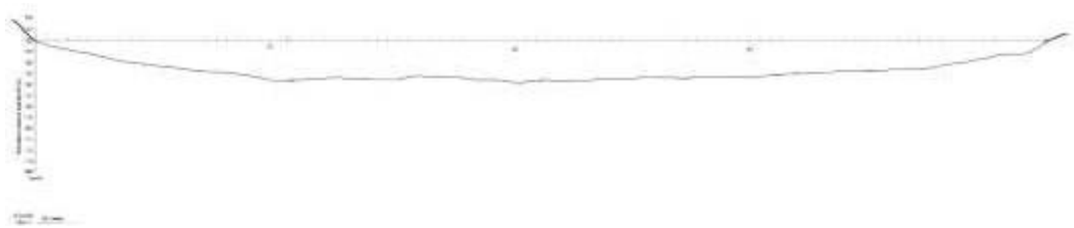
Figure 174: Bank and Vegetation

Figure 175: Open channel

Figure 176: Bank upstream stop 1

The Colorado River downstream of Austin was studied from Longhorn Dam to FM 973, approximately 11 miles downstream. River velocity is generally high here, resulting from water release from Longhorn Dam.

CR05 (in Austin):



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6):

2. Average Bank Angle (.6): 35^{o} (manmade)

3. Bank Cutting (.4): 1

4. Vegetative Bank Protection (.8): 5

5. Mass Wasting or Bank Failure (.8): 1 (Stabilized)

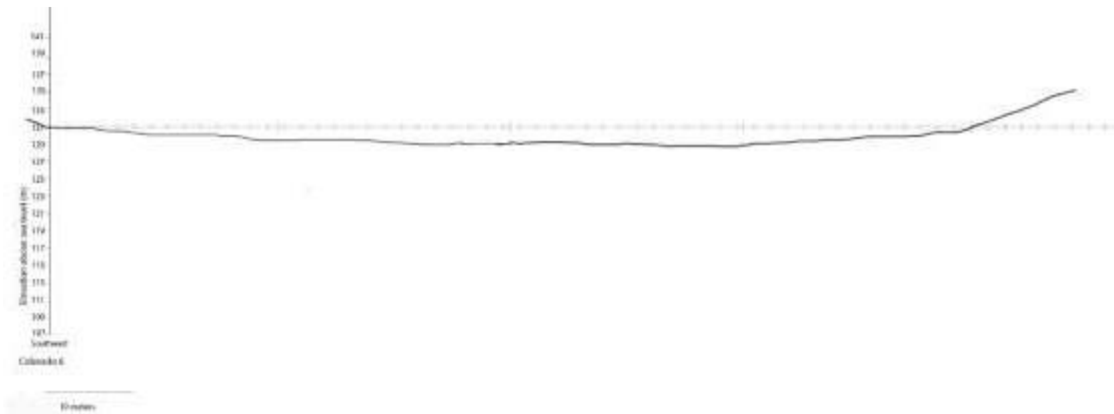
6. Bar Development (.6): 3

7. Debris-Jam Potential (.2): 1

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1

9. Channel material consolidation, armoring: 5

CR06:



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 9

2. **Average Bank Angle (.6):** 6^{O}-20^{O}, 11O

3. **Bank Cutting (.4):** 5

4. **Vegetative Bank Protection (.8):** 7

5. **Mass Wasting or Bank Failure (.8): 5**

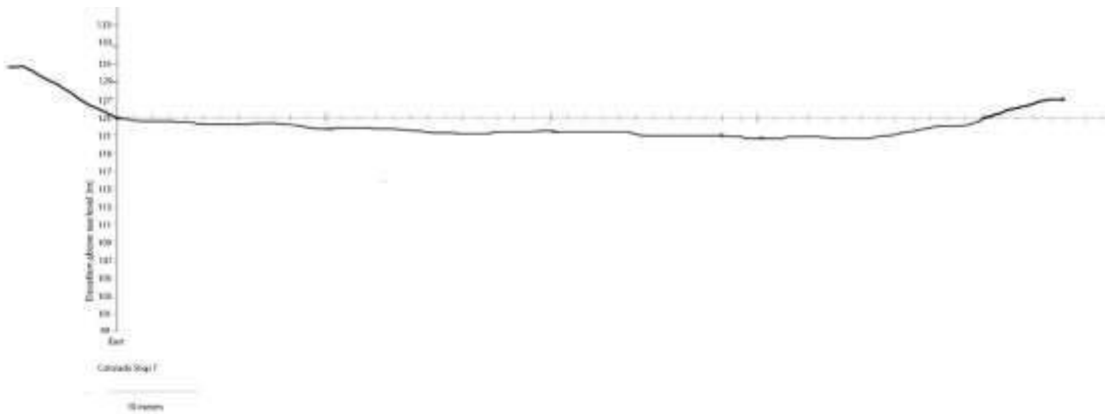
6. **Bar Development (.6): 1**

7. **Debris-Jam Potential (.2): 1**

8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 4**

9. **Channel material consolidation, armoring: 7**

CR07:



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 10

2. **Average Bank Angle (.6):** 3^{o}, 22^{o}

3. **Bank Cutting (.4):** 6

4. **Vegetative Bank Protection (.8):** 6

5. **Mass Wasting or Bank Failure (.8): 6**

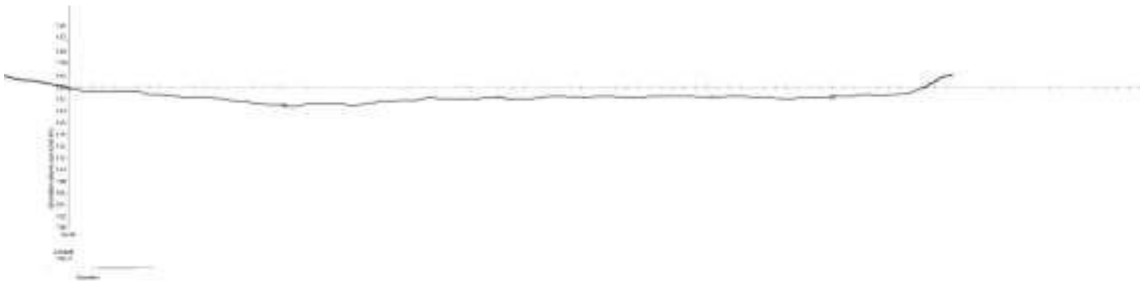
6. **Bar Development (.6): 9**

7. **Debris-Jam Potential (.2): 6**

8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 6**

9. **Channel material consolidation, armoring: 7**

CR08:



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 8, 5
2. **Average Bank Angle (.6):** 45^{o}-vertical
3. **Bank Cutting (.4):** 6
4. **Vegetative Bank Protection (.8):** 4
5. **Mass Wasting or Bank Failure (.8): 6**
6. **Bar Development (.6): 9**
7. **Debris-Jam Potential (.2): 6**
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 6**
9. **Channel material consolidation, armoring: 7**

Figure 177: Bank and vegetation

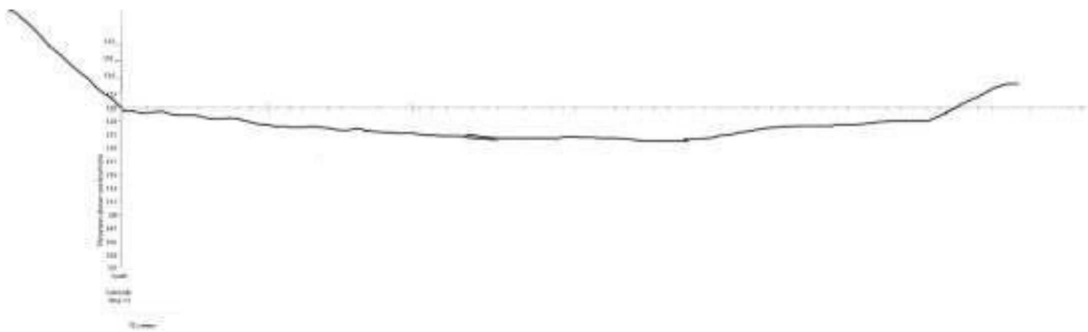
Figure 178: Debris in channel

CR09:

Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6): 4**
2. **Average Bank Angle (.6):** 28^{o}
3. **Bank Cutting (.4):** 4
4. **Vegetative Bank Protection (.8):** 4
5. **Mass Wasting or Bank Failure (.8): 4**
6. **Bar Development (.6): 8**
7. **Debris-Jam Potential (.2): 6**
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 6**
9. **Channel material consolidation, armoring: 7**

CR10:



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 3

2. Average Bank Angle (.6): 17°

3. Bank Cutting (.4): 3

4. Vegetative Bank Protection (.8): 3

5. Mass Wasting or Bank Failure (.8): 3

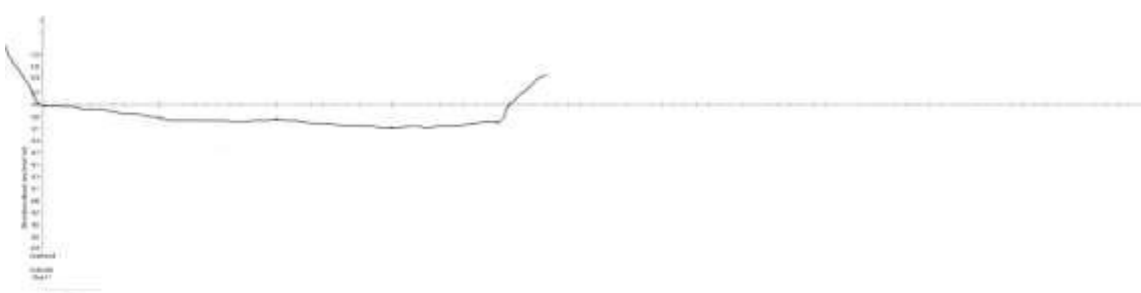
6. Bar Development (.6): 3

7. Debris-Jam Potential (.2): 3

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 3

9. Channel material consolidation, armoring: 7

CR11:



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 6

2. Average Bank Angle (.6): 22^{o}

3. Bank Cutting (.4): 5

4. Vegetative Bank Protection (.8): 4

5. Mass Wasting or Bank Failure (.8): 4

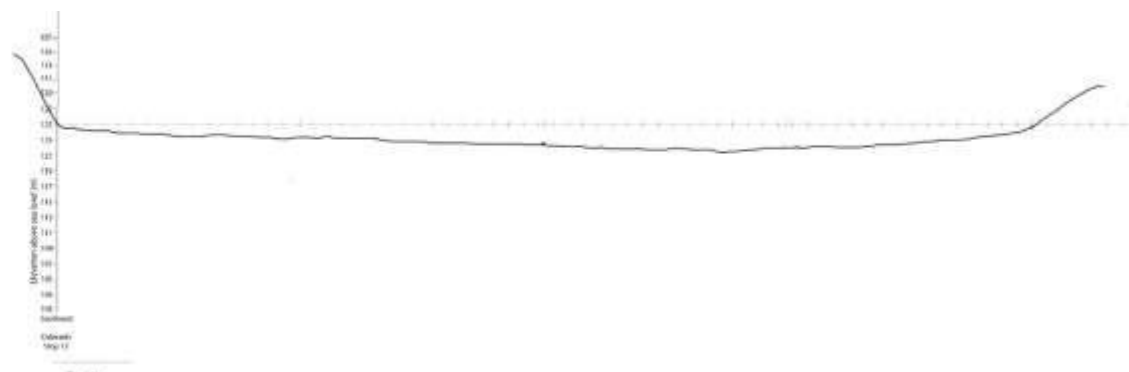
6. Bar Development (.6): 4

7. Debris-Jam Potential (.2): 3

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 5

9. Channel material consolidation, armoring: 7

CR12:



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 5

2. Average Bank Angle (.6): 12^{o}, 38^{o}

3. Bank Cutting (.4): 3

4. Vegetative Bank Protection (.8): 3

5. Mass Wasting or Bank Failure (.8): 3

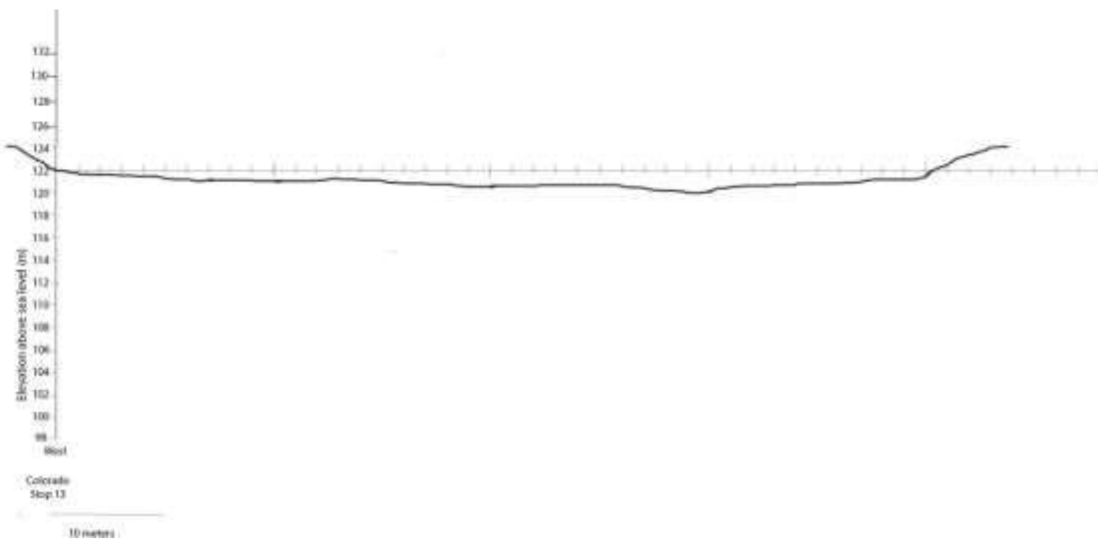
6. Bar Development (.6): 5

7. Debris-Jam Potential (.2): 5

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 5

9. Channel material consolidation, armoring: 7

CR13:



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): Limestone (solid)

2. Average Bank Angle (.6): Vertical

3. Bank Cutting (.4): NA

4. Vegetative Bank Protection (.8): NA

5. Mass Wasting or Bank Failure (.8): NA

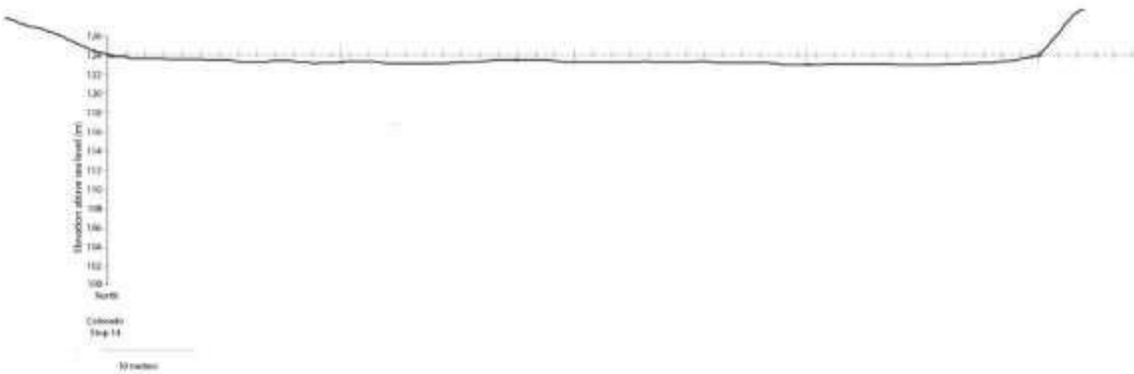
6. Bar Development (.6): 1

7. Debris-Jam Potential (.2): 1

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 1

9. Channel material consolidation, armoring: 7

CR14:



Assessment of Channel Stability:

1. Bank Soil Texture and Coherence (.6): 4

2. Average Bank Angle (.6): 50^{o}

3. Bank Cutting (.4): 10

4. Vegetative Bank Protection (.8): 10

5. Mass Wasting or Bank Failure (.8): 7

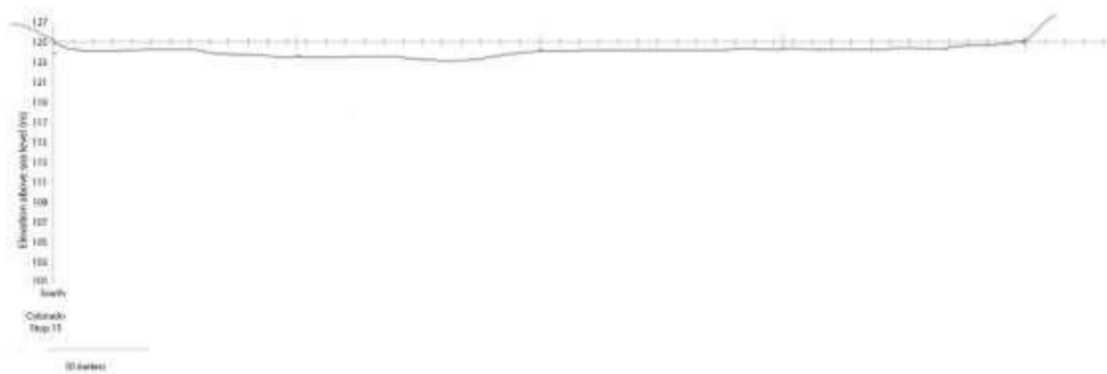
6. Bar Development (.6): 1

7. Debris-Jam Potential (.2): 1

8. Obstructions, Flow Deflectors, Sediment Traps (.2): 3

9. Channel material consolidation, armoring: 7

CR15:



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6): 8**

2. **Average Bank Angle (.6):** 15^{o}, vertical

3. **Bank Cutting (.4):** 4

4. **Vegetative Bank Protection (.8):** 6

5. **Mass Wasting or Bank Failure (.8): 3**

6. **Bar Development (.6): 1**

7. **Debris-Jam Potential (.2): 1**

8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 7**

9. **Channel material consolidation, armoring: 7**

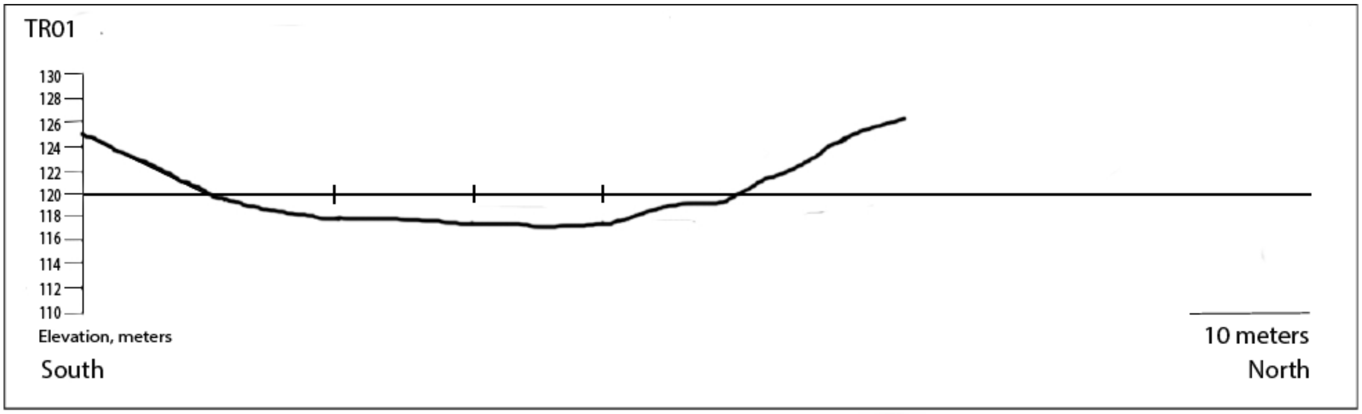
APPENDIX D

ASSESSMENTS OF CHANNEL STABILITY USING MORPHOLOGICAL INDICATORS: TRINITY RIVER NEAR DALLAS, TEXAS

A 5-mile reach of the Trinity River was studied, from its origin at the confluence of Elm Fork and West Fork west of Dallas and ending just downstream of Spur 366. At seven locations, a localized assessment of channel stability was made based upon the Modified Johnson et al. (1999) Method for Assessing Channel Stability, developed and used by Doyle et al. (2013).

TR01

Location TR01 is the confluence of Elm Fork and West Fork, marking the origin of the Trinity River in Texas. Construction was occurring at the time of these observations just upstream of the confluence.



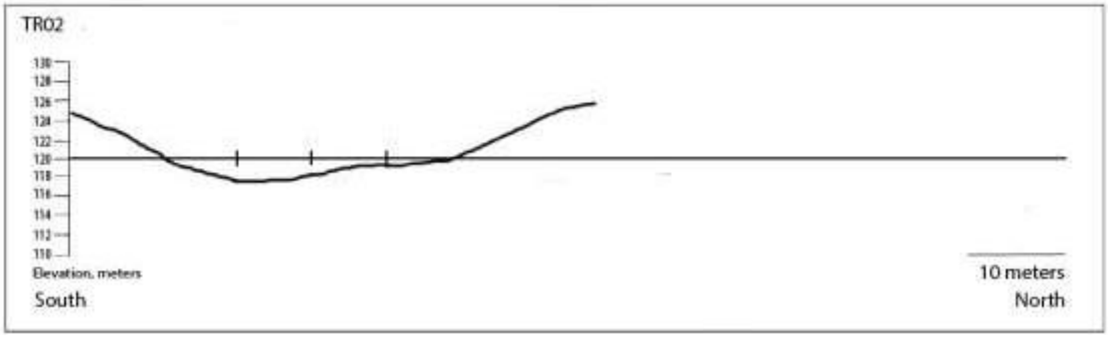
1. **Bank Soil Texture and Coherence (.6): 4**-Good.
2. **Average Bank Angle (.6):** 6-Good. Southern bank angle 26º, northern bank 26º.
3. **Bank Cutting (.4): 7**-Fair.
4. **Vegetative Bank Protection (.8): 6**-Good.
5. **Mass Wasting or Bank Failure (.8):** 4-Good.
6. **Bar Development (.6):** 6-Good.
7. **Debris-jam Potential (.2): 6**-Good. Debris accumulations occasional.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 5**-Good. None observed.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.
10. Channel Stability Score:
    (.6)(4)+(.6)(6)+(.4)(7)+(.8)(6)+(.8)(4)+(.6)(6)+(.2)(6)+(.2)(5)+(.8)(7)= 28.2

Figure 179: View upstream at the confluence of West Fork and Elm Fork

Figure 180: Cutting and bank failure at TR01. Cutting was not continuous, but serious where present.

TR02

Location TR02 is approximately 200 meters upstream of Westmoreland Rd.



1. **Bank Soil Texture and Coherence (.6): 7**-Fair.
2. **Average Bank Angle (.6):** 6-Good. Southern bank angle 26°, northern bank 26°.
3. **Bank Cutting (.4): 7**-Fair. Bank cutting not continuous, but vast where present.
4. **Vegetative Bank Protection (.8): 6**-Good.
5. **Mass Wasting or Bank Failure (.8):** 4-Good.
6. **Bar Development (.6):** 6-Good.
7. **Debris-jam Potential (.2): 10**-Poor. Debris accumulations prevalent.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 9**-Fair.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.

Channel Stability Score:

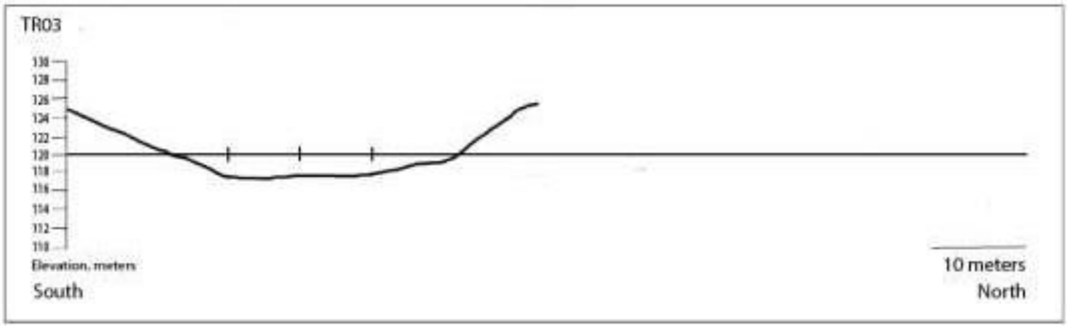
(.6)(7)+(.6)(6)+(.4)(7)+(.8)(6)+(.8)(4)+(.6)(6)+(.2)(10)+(.2)(9)+(.8)(7)= 31.6

Figure 181: Channel at TR02. Note lush vegetation on banks and extensive debris in channel.

Figure 182: TR02. Notice debris extending to bridge in background.

TR03

Location TR03 is halfway between Westmoreland Rd. and Inwood Rd.



1. **Bank Soil Texture and Coherence (.6): 4**-Good.
2. **Average Bank Angle (.6):** 6-Good. Southern bank angle 23°, northern bank 36°.
3. **Bank Cutting (.4): 7**-Fair.
4. **Vegetative Bank Protection (.8): 6**-Good.
5. **Mass Wasting or Bank Failure (.8):** 3-Excellent.
6. **Bar Development (.6):** 5-Good.
7. **Debris-jam Potential (.2): 10**-Poor. Debris accumulations prevalent.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 9**-Fair.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.

Channel Stability Score:

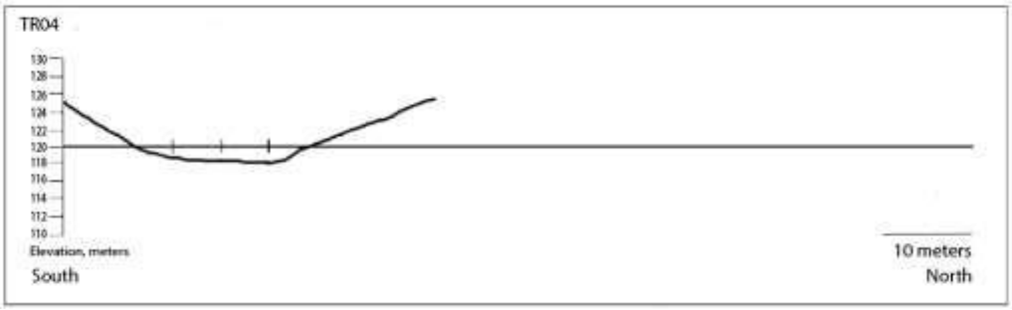
(.6)(4)+(.6)(6)+(.4)(7)+(.8)(6)+(.8)(3)+(.6)(5)+(.2)(10)+(.2)(9)+(.8)(7)= 28.4

Figure 183: Leaning vegetation at TR03

Figure 184: River channel at TR03

TR04

Location TR04 is halfway between and Inwood Rd. and Sylvan Ave.



1. **Bank Soil Texture and Coherence (.6): 3**-Excellent. Shale is present nearest the water, becomes sandier up the bank.
2. **Average Bank Angle (.6):** 7-Fair. Southern bank angle 30º, northern bank 32º.
3. **Bank Cutting (.4): 8**-Fair.
4. **Vegetative Bank Protection (.8): 7**-Fair. Vegetation is plentiful, but grassy. Mix of soft wood (willows) and hard wood (oak). Several trees are leaning, with exposed roots.
5. **Mass Wasting or Bank Failure (.8):** 6-Good. Mass wasting is infrequent.
6. **Bar Development (.6):** 5-Good.
7. **Debris-jam Potential (.2): 7**-Fair.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 7**-Fair.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.

Channel Stability Score:

(.6)(3)+(.6)(7)+(.4)(8)+(.8)(7)+(.8)(6)+(.6)(5)+(.2)(7)+(.2)(7)+(.8)(7)= 31

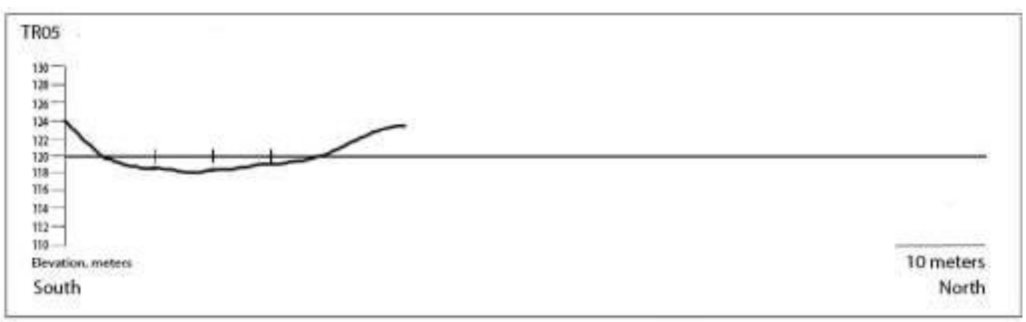
Figure 185: View of channel at TR04. Notice debris in background.

Figure 186: Bank cutting and failure at TR04.

Figure 187: Bank at TR04. Notice abundant, grassy vegetation and slight mass wasting.

TR05

Location TR05 is located at the Trammel Crow Public Boat Ramp at Trammel Crow Park off of Sylvan Ave.



1. **Bank Soil Texture and Coherence (.6): 1**-Excellent. Extremely clay rich. Frustratingly clayey.

2. **Average Bank Angle (.6):** 6-Good. Southern bank angle 45^{o}, northern bank 23^{o}.
3. **Bank Cutting (.4): 4**-Good. Some bare banks are visible, but this is likely a result of low water (observations were made in July 2018).
4. **Vegetative Bank Protection (.8): 5**-Good. Vegetation is plentiful, but grassy.
5. **Mass Wasting or Bank Failure (.8):** 4-Good.
6. **Bar Development (.6):** 5-Good.
7. **Debris-jam Potential (.2): 6**-Good. Occasional debris, but not severe.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 5**-Good.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.

Channel Stability Score:

(.6)(1)+(.6)(6)+(.4)(4)+(.8)(5)+(.8)(4)+(.6)(5)+(.2)(6)+(.2)(5)+(.8)(7)= 23.8

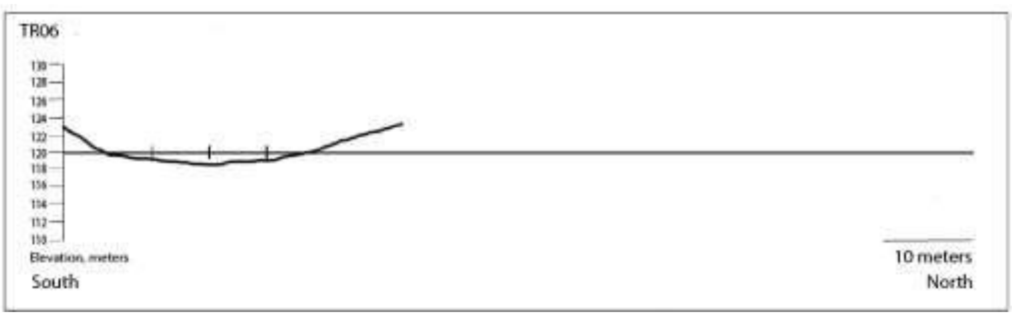
Figure 188: Southern bank at TR05. Notice trees leaning away from river channel and significant undercutting.

Figure 189: Close-up of undercutting on TR05 southern bank.

Figure 190: River channel at TR05, looking downstream.

TR06

Location TR06 is located about 150 meters upstream of the Spur 366 suspension bridge.



1. **Bank Soil Texture and Coherence (.6): 3-**Excellent. Extremely clay rich.
2. **Average Bank Angle (.6):** 4-Good. Southern bank angle 35^{o}, northern bank 17^{o}.
3. **Bank Cutting (.4): 4-**Good.
4. **Vegetative Bank Protection (.8): 5-**Good. Some trees are leaning.

5. **Mass Wasting or Bank Failure (.8):** 4-Good.
6. **Bar Development (.6):** 4-Good.
7. **Debris-jam Potential (.2): 6**-Good. Occasional debris, but not severe.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 5**-Good.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.

Channel Stability Score:

(.6)(3)+(.6)(4)+(.4)(4)+(.8)(5)+(.8)(4)+(.6)(4)+(.2)(6)+(.2)(5)+(.8)(7)= 23.2

Figure 191: Northern bank at TR06. Note grassy vegetation; barren banks likely result of low water in this instance.

Figure 192: Leaning vegetation and undercutting on southern bank at TR06.

Figure 193: Slump on northern bank at TR06

Figure 194: Scalloping layers on southern bank at TR06

TR07

Location TR07 is located just downstream of the Spur 366 suspension bridge, upstream of a railroad trellis.

1. **Bank Soil Texture and Coherence (.6): 3**-Excellent.
2. **Average Bank Angle (.6):** 5-Good. Southern bank angle 26º, northern bank 23º.
3. **Bank Cutting (.4): 4**-Good.
4. **Vegetative Bank Protection (.8): 5**-Good. Some trees are leaning.
5. **Mass Wasting or Bank Failure (.8):** 5-Good.
6. **Bar Development (.6):** 6-Good.
7. **Debris-jam Potential (.2): 7**-Fair.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 6**-Good.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.

Channel Stability Score:

(.6)(3)+(.6)(5)+(.4)(4)+(.8)(5)+(.8)(5)+(.6)(6)+(.2)(7)+(.2)(6)+(.8)(7)= 26.2

Figure 195: Southern bank at TR07

Figure 196: Undercutting exposed by low water at TR07

Figure 197: View downstream at TR07. Notice reduced vegetation and increased debris.

Trinity River, Trinity Standing Wave Whitewater to Loop 12

Location 1 was within 200 meters of the put-in at the Trinity Standing Wave Whitewater and the Santa Fe Railroad Trestle.

Figure 198: Cross Section of Trinity River at Location 1.
Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 7-Fair. Layered on limestone bedrock, sediment consists of sandy-clay loam with many cobbles, though the cobbles were likely brought in for construction and stabilization of the railroad trestle, standing wave, and hiking trails.
2. **Average Bank Angle (.6):** 9-Fair. Average bank angle along this section is 45-55 degrees from horizontal. Figure 5 shows the typical appearance of banks along this stretch.
3. **Bank Cutting (.4):** 10-Poor. Banks regularly are bare beyond 60 cm. Exposed roots are common.
4. **Vegetative Bank Protection (.8):** 7-Fair. The banks, where vegetated, are well vegetated. Concerns are exposed roots and occasional trees which are tilted 10-20 degrees from vertical though these are not excessive on this reach.

5. **Mass Wasting or Bank Failure (.8):** 9-Fair. Frequent earthflows and scalloping on channel walls
6. **Bar Development (.6):** 8-Fair. Bars are unvegetated and consist of sand and cobbles.
7. **Debris-Jam Potential (.2):** 5-Good. Small accumulations of debris make debris jams possible, particularly during flood events. Some of this debris is woody debris from the adjoining vegetation, and significant amounts are of an anthropogenic source.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 4-Good. None observed.
9. **Channel-bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Overall stability score of Location 1 is

(.6)(7)+(.6)(9)+(.4)(10)+(.8)(7)+(.8)(9)+(.2)(5)+(.2)(4)+(.8)(5)= 32.2.

Stop 1:

Bank sediment at put-in, Santa Fe Trestle

Banks at Location 1

Exposed Roots

Exposed Roots at Location 1

Scalloping of banks at Location 1

Location 2:

Location 2 is a straight reach bounded by two meanders just west of the Cedar Crest Blvd. overpass. A cross section of Location 2 is presented in Figure 18.

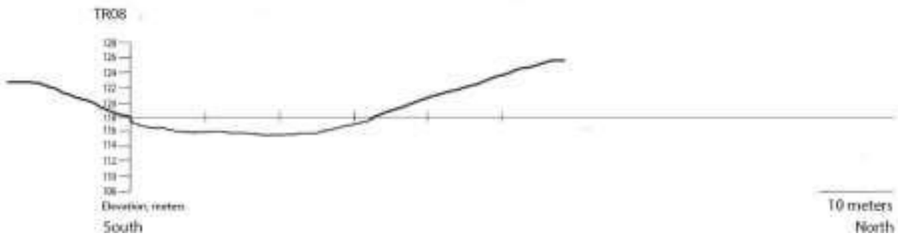
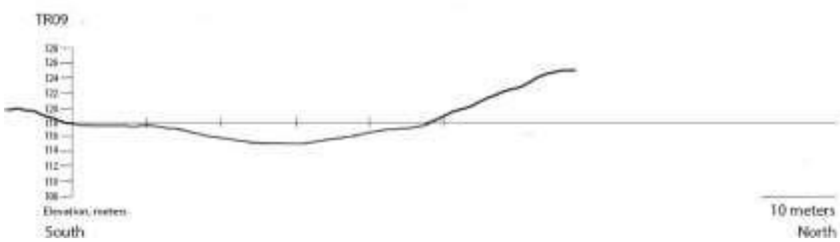


Figure 199: Cross Section of Location 2

No formal assessment of channel stability was performed here, as the proximity to Location 1 resulted in very similar conditions.

Location 3:

Location 3 is a straight reach west of the DFW Subdivision railroad trestle.



Assessment of Channel Stability:

1. **Bank Soil Texture and Coherence (.6):** 6-Good. Banks are clay-rich with fine sand present, especially in the southern bank.
2. **Average Bank Angle (.6):** 6-Good. Northern bank slopes at 44 degree angle, southern bank at 15 degree angle.

3. **Bank Cutting (.4):** 10-Poor. Continuous cuts with bare banks over 60 cm.
4. **Vegetative Bank Protection (.8):** 9-Fair. Vegetation on the northern bank is angled 70-80 degrees from horizontal, but on the southern bank ranges from vertical to 45 degrees from horizontal. Exposed roots prevalent on both sides.
5. **Mass Wasting or Bank Failure (.8):** 10-Poor. Scalloping and earthflows are common and moderate.
6. **Bar Development (.6):** 8-Fair. Young bars with no vegetation.
7. **Debris-jam Potential (.2):** 9-Fair. Debris accumulations present in channel, but remain small.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 4-Good. None observed.
9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

(.6)(6)+(.6)(6)+(.4)(10)+(.8)(9)+(.8)(8)+(.6)(10)+(.2)(9)+(.2)(4)+(.8)(5) = 37.4

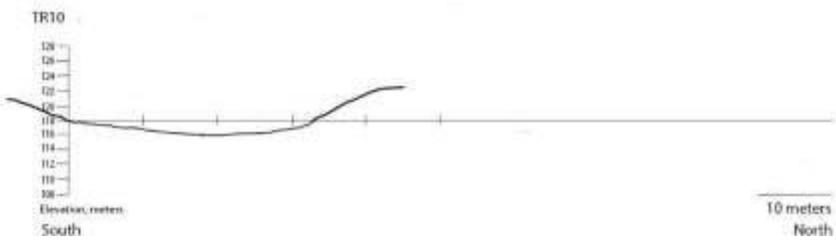
Barren banks at Location 3

Angled vegetation on southern bank of Location 3.

Earthflow at Location 3

Location 4

Location 4 is a straight reach to the east of the DFW Subdivision railroad trestle.



1. **Bank Soil Texture and Coherence (.6):** 3-Excellent. Immediately after trestle, bedded limestone ~6 ft. (2 meters) thick is topped by clays and conglomerates. Limestone bedding abruptly ends at channel’s southward turn and banks are composed of clay.
2. **Average Bank Angle (.6):** 8-Fair. 44^{o}
3. **Bank Cutting (.4):** 10-Poor. Continuous cuts with bare banks over 60 cm.
4. **Vegetative Bank Protection (.8):** 10-Poor. Vegetation lacking on bedded limestone. Though abundant grass on overlying sediment, exposed tree roots are common and many trees drastically angled.
5. **Mass Wasting or Bank Failure (.8):** 9-Fair. Scalloping and earthflows are common.
6. **Bar Development (.6):** 8-Fair. Young bars with no vegetation.
7. **Debris-jam Potential (.2):** 9-Fair. Debris accumulations present in channel, but remain small.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 4-Good. None observed.

9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

(.6)(3)+(.6)(8)+(.4)(10)+(.8)(10)+(.8)(9)+(.6)(8)+(.2)(9)+(.2)(4)+(.8)(5) = 37.2

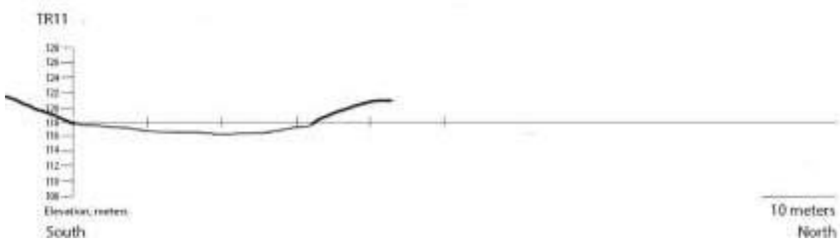
Bedded limestone and bank sediment at Location 4.

Bank at Location 4 just after bedded limestone.

Recent earthflow at Location 4.

Location 5:

Location 5 is the first southward-trending reach following the DFW Subdivision railroad trestle.



1. **Bank Soil Texture and Coherence (.6):** 6-Good. Banks are clay-rich with fine sand present.
2. **Average Bank Angle (.6):** 8-Fair. 44^{o}
3. **Bank Cutting (.4):** 10-Poor. Continuous cuts with bare banks over 60 cm.
4. **Vegetative Bank Protection (.8):** 7-Fair. The banks, where vegetated, are well vegetated. Exposed roots common.
5. **Mass Wasting or Bank Failure (.8):** 9-Fair. Scalloping and earthflows are common.
6. **Bar Development (.6):** 9-Fair. Young bars with no vegetation.
7. **Debris-jam Potential (.2):** 9-Fair. Debris accumulations present in channel, but remain small.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 4-Good. None observed.
9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

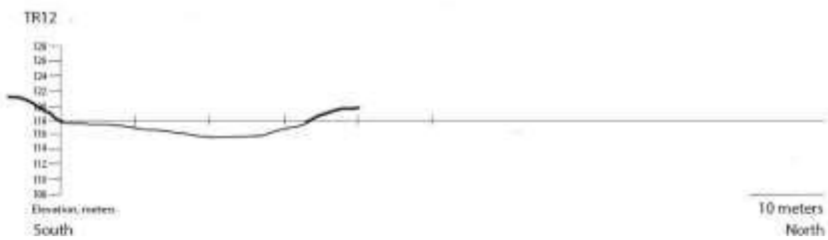
(.6)(6)+(.6)(8)+(.4)(10)+(.8)(7)+(.8)(9)+(.6)(9)+(.2)(9)+(.2)(4)+(.8)(5)= 35.4

Figure 13: Mass Wasting at Location 5

Figure 14: Banks at Location 5

Location 6:

Location 6 marks a northward turn of the river channel.



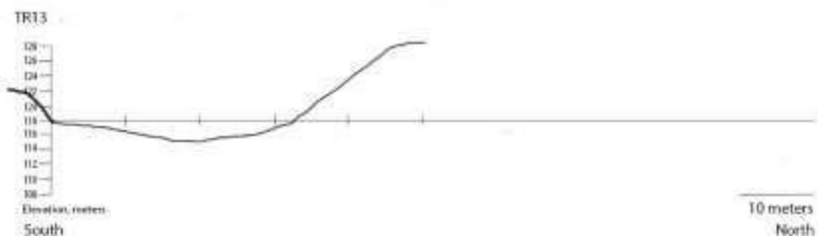
1. **Bank Soil Texture and Coherence (.6):** 9-Fair. Loosely packed clay and sand.
2. **Average Bank Angle (.6):** 6-Good. Southern bank angle is 60°, northern bank angle is 15° on the bar and 26° above.
3. **Bank Cutting (.4):** 12-Poor. Continuous cuts at least 60 cm high..
4. **Vegetative Bank Protection (.8):** 3-Excellent. Banks are well vegetated, heavily at top. Trees are vertical.
5. **Mass Wasting or Bank Failure (.8):** 8-Fair. Scalloping and earthflows are common.
6. **Bar Development (.6):** 9-Fair. Young bars with no vegetation.
7. **Debris-jam Potential (.2):** 9-Fair. Debris accumulations present in channel, but remain small.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 4-Good. None observed.
9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

(.6)(9)+(.6)(6)+(.4)(12)+(.8)(3)+(.8)(8)+(.6)(9)+(.2)(9)+(.2)(4)+(.8)(5) = 34.6

Location 7

Location is a straight reach trending S45E, parallel to I-45.



1. **Bank Soil Texture and Coherence (.6):** 9-Fair. Loosely packed clay and sand on top of bedded limestone.

2. **Average Bank Angle (.6):** 6-Good. Southern bank angle is 14^{o}, northern bank angle is 30^{o}

3. **Bank Cutting (.4):** 4-Poor. Continuous cuts at least 60 cm high.

4. **Vegetative Bank Protection (.8):** 7-Fair. Banks are well vegetated, heavily at top, but trees are angled and roots exposed.

5. **Mass Wasting or Bank Failure (.8):** 7-Fair. Scalloping and earthflows are common.

6. **Bar Development (.6): 10**-Poor. Young bars with no vegetation.

7. **Debris-jam Potential (.2):** 7-Fair. Debris accumulations present in channel, but remain small.

8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 4-Good. None observed.

9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

(.6)(9)+(.6)(6)+(.4)(4)+(.8)(7)+(.8)(7)+(.6)(10)+(.2)(7)+(.2)(4)+(.8)(5) = 34

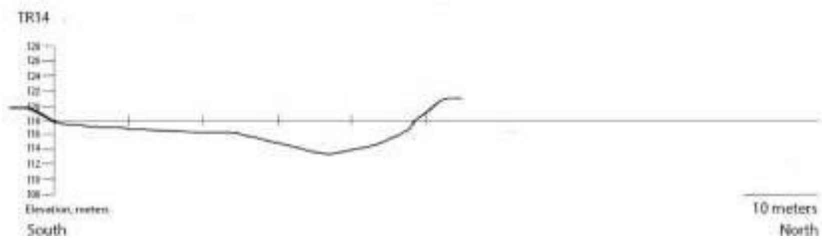
Figure 15: Banks at Location 7

Figure 16: Angled trees at Location 7

Figure 17: Earthflow at Location 7

Location 8

Location 8 is a straight reach within 300 m of the I-45 overpass.



1. **Bank Soil Texture and Coherence (.6):** 3-Excellent. Cohesive clay.
2. **Average Bank Angle (.6):** 7-Fair. Southern bank angle is 71°, northern bank angle is 17°
3. **Bank Cutting (.4):** 4-Poor. Continuous cuts at least 60 cm high.
4. **Vegetative Bank Protection (.8):** 4-Good. Banks are well vegetated, heavily at top. Trees are vertical.
5. **Mass Wasting or Bank Failure (.8):** 4-Good. Rarely noticeable.
6. **Bar Development (.6):** 7-Fair. Some young bars with no vegetation.
7. **Debris-jam Potential (.2):** 9-Fair. Debris accumulations more prevalent.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 4-Good. None observed.
9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

(.6)(3)+(.6)(7)+(.4)(4)+(.8)(4)+(.8)(4)+(.6)(7)+(.2)(9)+(.2)(4)+(.8)(5) = 24.8

Location 8

Figure 18: Banks at Location 8.

Figure 19: Debris near Location 8

Location 9

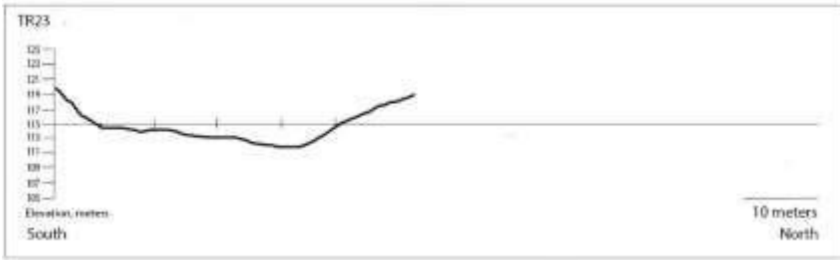
Location 9 is a portion of a straight reach immediately southeast of the I-45 overpass. It stood out because of the wider bars than had been seen in other locations.

1. **Bank Soil Texture and Coherence (.6):** 9-Fair. Loose clay and sand.
2. **Average Bank Angle (.6):** 4-Good. Southern banks angle 11^{o}, northern bank 29^{o}.
3. **Bank Cutting (.4):** 8-Poor. Continuous cuts at least 60 cm high.
4. **Vegetative Bank Protection (.8):** 10-Poor. Widely unvegetated banks.
5. **Mass Wasting or Bank Failure (.8):** 9-Fair. Earthflows noticeable.
6. **Bar Development (.6):** 9-Fair. Wide, young bars with no vegetation.
7. **Debris-jam Potential (.2):** 7-Fair. Debris accumulations occasional.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 4-Good. None observed.
9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

(.6)(9)+(.6)(4)+(.4)(8)+(.8)(10)+(.8)(9)+(.6)(9)+(.2)(7)+(.2)(4)+(.8)(5) = 37

Location 10

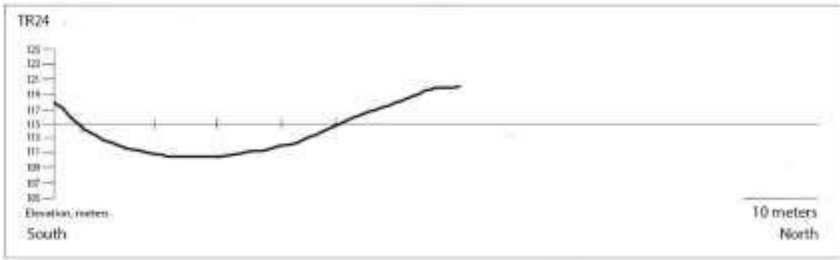


11. **Bank Soil Texture and Coherence (.6):** 3-Excellent. Clay.
12. **Average Bank Angle (.6):** 6-Good. Southern bank angle 20^o, northern bank 50^o.
13. **Bank Cutting (.4):** 8-Poor. Continuous cuts at least 60 cm high.
14. **Vegetative Bank Protection (.8):** 8-Fair.
15. **Mass Wasting or Bank Failure (.8):** 9-Fair. Earthflows noticeable.
16. **Bar Development (.6):** 9-Fair. Wide, young bars with no vegetation.
17. **Debris-jam Potential (.2):** 7-Fair. Debris accumulations occasional.
18. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 4-Good. None observed.
19. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

(.6)(3)+(.6)(6)+(.4)(8)+(.8)(8)+(.8)(9)+(.6)(9)+(.2)(7)+(.2)(4)+(.8)(5)= 33.8

Location 11



1. **Bank Soil Texture and Coherence (.6):** 3-Excellent. Clay.
2. **Average Bank Angle (.6):** 4-Good. Southern bank angle 26^{o}, northern bank 20^{o}.
3. **Bank Cutting (.4):** 8-Fair. Continuous cuts at least 60 cm high.
4. **Vegetative Bank Protection (.8):** 8-Fair. .
5. **Mass Wasting or Bank Failure (.8):** 11-Fair. Earthflows noticeable, with visible slump blocks.
6. **Bar Development (.6):** 9-Fair. Young bars with no vegetation.
7. **Debris-jam Potential (.2):** 10-Poor. Debris accumulations prevalent.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 9-Fair. Cross currents prevalent.
9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

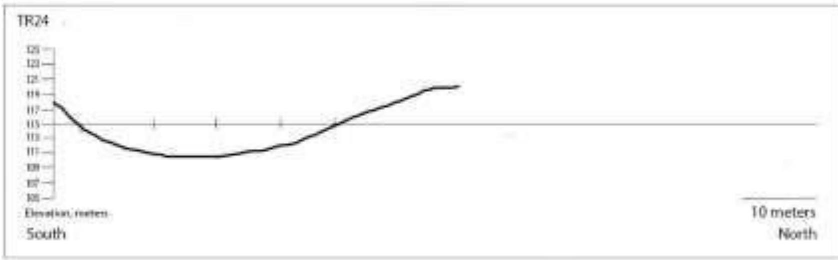
Channel Stability Score:

(.6)(3)+(.6)(4)+(.4)(8)+(.8)(8)+(.8)(11)+(.6)(9)+(.2)(10)+(.2)(9)+(.8)(5)= 35.8

Stop 11

Figure 20: Slump blocks

Location 12



1. **Bank Soil Texture and Coherence (.6):** 6-Good. Clay, sand, loam.

2. **Average Bank Angle (.6): 5**-Good. Southern bank angle 25^{o}, northern bank 10^{o}.

3. **Bank Cutting (.4):** 7-Fair.

4. **Vegetative Bank Protection (.8):** 7-Fair.

5. **Mass Wasting or Bank Failure (.8):** 7-Fair.

6. **Bar Development (.6):** 8-Fair.

7. **Debris-jam Potential (.2):** 8-Fair. Debris accumulations more prevalent.

8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 6-Good.

9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

(.6)(6)+(.6)(5)+(.4)(7)+(.8)(7)+(.8)(7)+(.6)(8)+(.2)(8)+(.2)(6)+(.8)(5)= 32.2

Location 13

1. **Bank Soil Texture and Coherence (.6):** 6-Good. Clay and sandy clay.

2. **Average Bank Angle (.6):** 4-Good. Southern bank angle 20°, northern bank 32°.

3. **Bank Cutting (.4):** 7-Fair.

4. **Vegetative Bank Protection (.8):** 5-Good.

5. **Mass Wasting or Bank Failure (.8):** 5-Good.

6. **Bar Development (.6):** 6-Good. Increasingly vegetated bars.

7. **Debris-jam Potential (.2):** 6-Good.

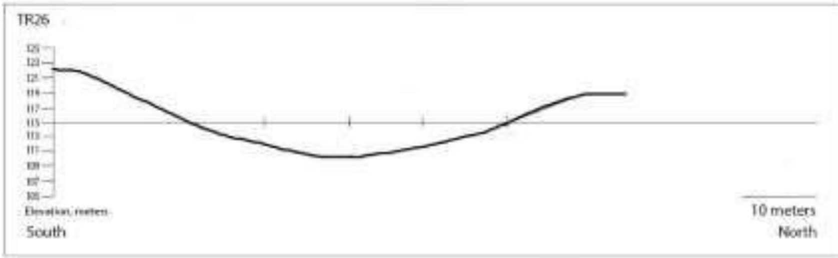
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 6-Good.

9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel stability score:

(.6)(6)+(.6)(4)+(.4)(7)+(.8)(5)+(.8)(5)+(.6)(6)+(.2)(6)+(.2)(6)+(.8)(5)= 26.8

Location 14



1. **Bank Soil Texture and Coherence (.6):** 6-Good. Clay and sandy clay.
2. **Average Bank Angle (.6):** 4-Good. Southern bank angle 12^{o}, northern bank 28^{o}.
3. **Bank Cutting (.4):** 7-Fair.
4. **Vegetative Bank Protection (.8):** 5-Good.
5. **Mass Wasting or Bank Failure (.8):** 7-Fair.
6. **Bar Development (.6):** 6-Good.
7. **Debris-jam Potential (.2):** 7-Fair.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 6-Good.
9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

Channel Stability Score:

(.6)(6)+(.6)(4)+(.4)(7)+(.8)(5)+(.8)(7)+(.6)(6)+(.2)(7)+(.2)(6)+(.8)(5)= 28.6

Location 15

1. **Bank Soil Texture and Coherence (.6):** 5-Good. Clay and sandy clay, gravel.
2. **Average Bank Angle (.6):** 6-Good. Eastern bank angle 11º, western bank 40º.
3. **Bank Cutting (.4):** 7-Fair.
4. **Vegetative Bank Protection (.8):** 2-Excellent.
5. **Mass Wasting or Bank Failure (.8):** 5-Good.
6. **Bar Development (.6):** 6-Good.
7. **Debris-jam Potential (.2):** 2-Excellent.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2):** 6-Good.
9. **Channel-Bed Material Consolidation and Armoring (.8):** 5-Good. Channel beds are made of well consolidated, fine grained sediment.

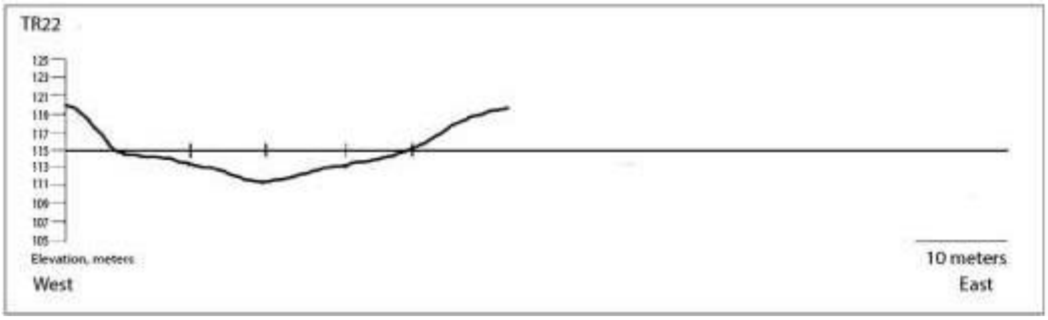
Channel Stability Score:

(.6)(5)+(.6)(6)+(.4)(7)+(.8)(2)+(.8)(5)+(.6)(6)+(.2)(2)+(.2)(6)+(.8)(5)= 24.2

Trinity River – Loop 12 to McCommas Bluff

A 3.6 mile stretch of the Trinity River from Loop 12 into the Great Trinity Forest was studied. This provided an opportunity for assessing stability differences, if any, in the river channel with increasing distance from the Dallas urban center. The Great Trinity Forest is a 6,000 acre bottomland forest which borders the Trinity River for approximately 11 miles.

TR22



1. **Bank Soil Texture and Coherence (.6): 1**-Excellent.

2. **Average Bank Angle (.6): 7**-Fair.

3. **Bank Cutting (.4): 8**-Fair.

4. **Vegetative Bank Protection (.8): 6**-Good.

5. **Mass Wasting or Bank Failure (.8):** 6-Good.

6. **Bar Development (.6):** 6-Good.

7. **Debris-jam Potential (.2): 10**-Poor.

8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 10**-Poor.

9. **Channel-Bed Material Consolidation and Armoring (.8): 8**-Fair.

Total: 1(.6) + 7(.6) + 8(.4) + 6(.8) + 6(.8) + 6(.6) + 10(.2) + 10(.2) + 8(.8) = 31.6

Figure 200: Debris in river channel

Figure 201: Leaning vegetation and exposed banks

Figure 203: Exposed bank and exposed roots

Figure 202: Debris

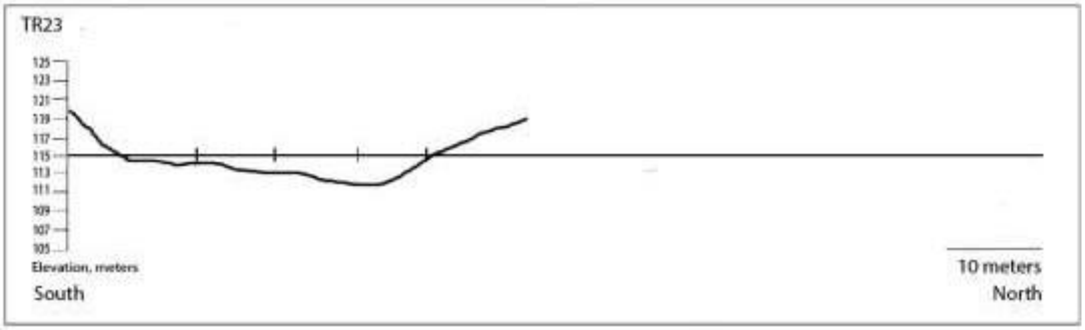
Figure 204: Notice turbulence in foreground

Figure 205: Extensive vegetation, but young

Figure 207: Young vegetation, fallen trees

Figure 206: Scalloping layers

TR23



1. **Bank Soil Texture and Coherence (.6): 1**-Excellent.

2. **Average Bank Angle (.6): 7**-Fair.

3. **Bank Cutting (.4): 8**-Fair.

4. **Vegetative Bank Protection (.8): 9**-Poor.

5. **Mass Wasting or Bank Failure (.8):** 7-Fair.

6. **Bar Development (.6):** 4-Good.

7. **Debris-jam Potential (.2): 8**-Poor.

8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 7**-Fair.

9. **Channel-Bed Material Consolidation and Armoring (.8): 8**-Fair.

Total: 1(.6) + 7(.6) + 8(.4) + 9(.8) + 7(.8) + 4(.6) + 8(.2) + 7(.2) + 8(.8) = 32.6

Figure 209: Channel at Stop 2; Notice increasing vegetation and debris

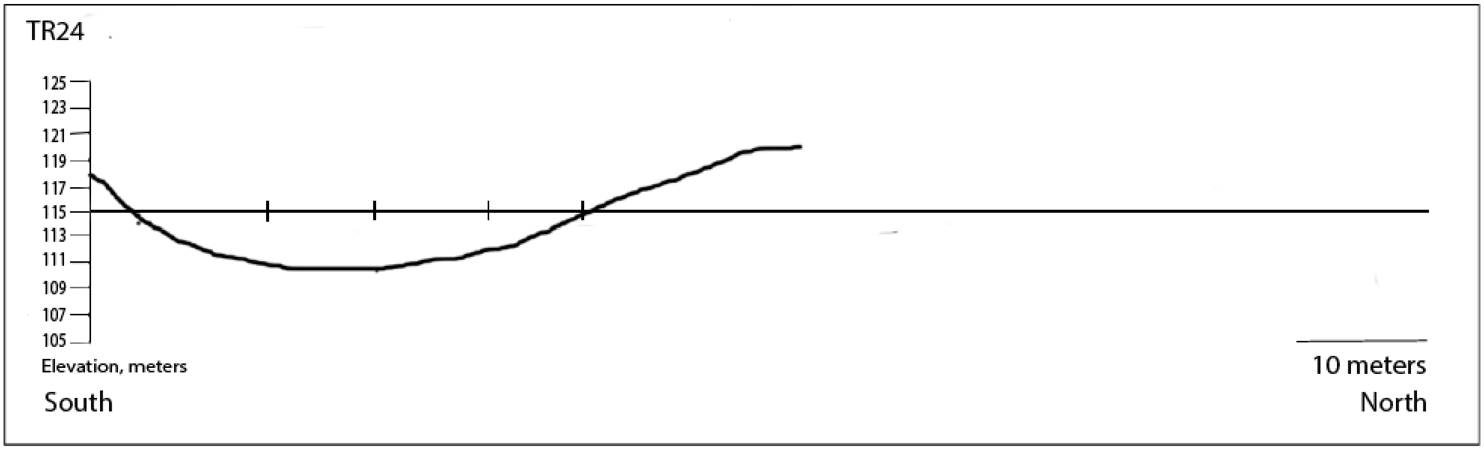
Figure 208: Exposed roots near Stop 2

Figure 211: Banks near Stop 2

Figure 210: Debris near Stop 2

Figure 212: Small slump near Stop 2

TR24



1. **Bank Soil Texture and Coherence (.6): 1**-Excellent.
2. **Average Bank Angle (.6): 7**-Fair.
3. **Bank Cutting (.4): 10**-Poor.
4. **Vegetative Bank Protection (.8): 6**-Good.
5. **Mass Wasting or Bank Failure (.8):** 7-Fair.
6. **Bar Development (.6):** 6-Good.
7. **Debris-jam Potential (.2): 10**-Poor.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 8**-Fair.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.

   Total: 1(.6) + 7(.6) + 10(.4) + 6(.8) + 7(.8) + 6(.6) + 10(.2) + 8(.2) + 7(.8) =

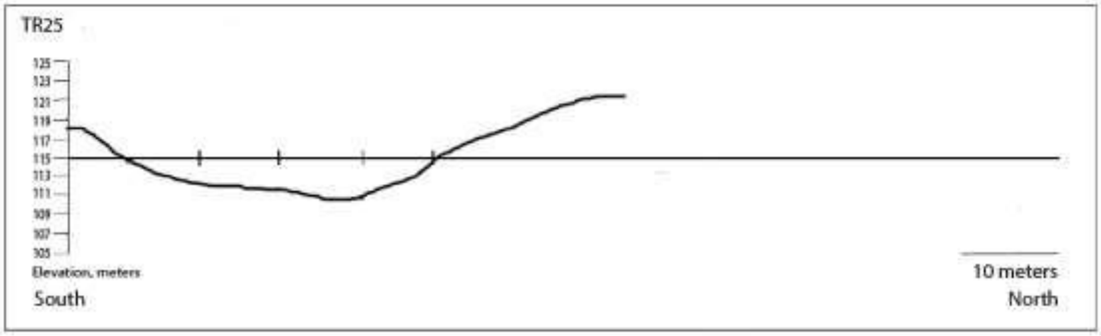
   29.72

Slightly scalloping layers near Location 3

Bank near Location 3; notice exposed bank, slightly angled trees, and debris

Figure 213: Scalloping Banks near Location 3

TR25



1. **Bank Soil Texture and Coherence (.6): 1**-Excellent.
2. **Average Bank Angle (.6): 6**-Good.
3. **Bank Cutting (.4): 7**-Fair.
4. **Vegetative Bank Protection (.8): 8**-Fair.
5. **Mass Wasting or Bank Failure (.8):** 6-Good.
6. **Bar Development (.6):** 6-Good.
7. **Debris-jam Potential (.2): 10**-Poor.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 8**-Fair.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.

Total: 1(.6) + 6(.6) + 7(.4) + 8(.8) + 6(.8) + 6(.6) + 10(.2) + 8(.2) + 7(.8) = 31

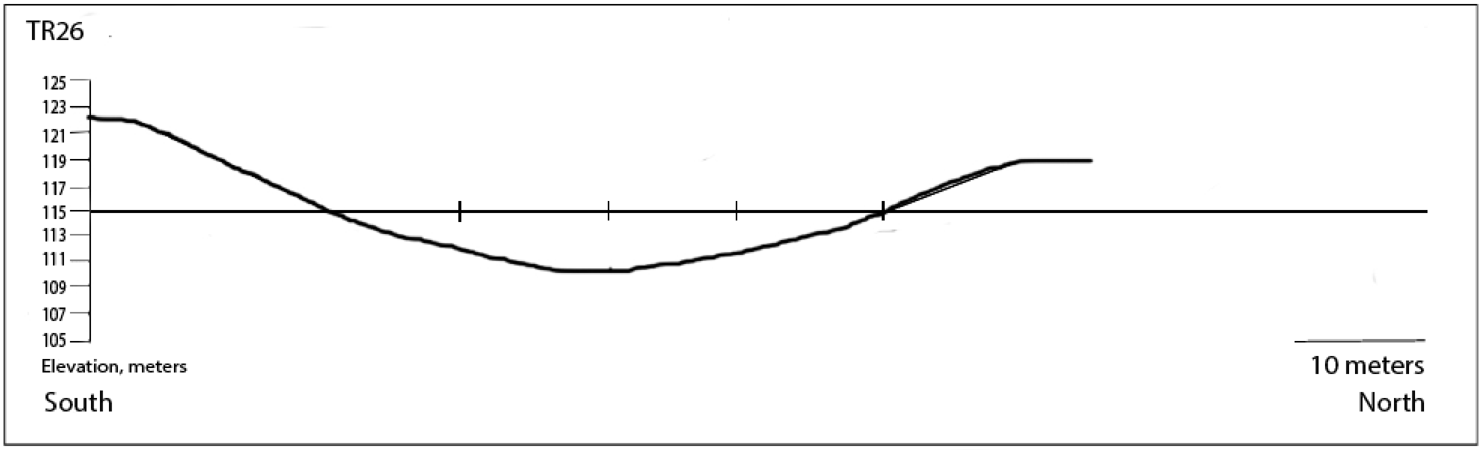
Figure 214: Channel near Location 4

Bank near Location 4; notice leaning vegetation closest to bank, small slump to left of frame

Close-up of bank near Location 4. Bank was extremely clay-rich.

Location 5

TR26



1. **Bank Soil Texture and Coherence (.6): 1**-Excellent.
2. **Average Bank Angle (.6): 5**-Good.
3. **Bank Cutting (.4): 7**-Fair.
4. **Vegetative Bank Protection (.8): 5**-Good.
5. **Mass Wasting or Bank Failure (.8):** 6-Good.
6. **Bar Development (.6):** 4-Good.
7. **Debris-jam Potential (.2): 3**-Excellent.
8. **Obstructions, Flow Deflectors, Sediment Traps (.2): 3**-Excellent.
9. **Channel-Bed Material Consolidation and Armoring (.8): 7**-Fair.

Total: 1(.6) + 5(.6) + 7(.4) + 5(.8) + 6(.8) + 4(.6) + 3(.2) + 3(.2) + 7(.8) = 24.4

Location 5

Some reaches near Location 5 had mature vegetation, nearly vertical, close to the water.

Other sections had increased channel erosion with exposed roots.

Leaning vegetation

Small slump near Location 5.

Figure 215: Channel near Location 5

Debris near Location 6. Note the increased vegetation on banks.

Exposed banks remain prevalent in some stretches near Location 6.

Figure 216: Banks near Location 6