Geomorphic Classification of the Lower San Antonio River, Texas

Texas Water Development Board
Project 0604830637

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TABLE OF CONTENTS Page

LIST OF TABLES **PAGE**

LIST OF FIGURES **PAGE**

Project Task Summary

The tasks outlined in the "Tasks" section of the Scope of Work were completed. The chart below shows where the descriptions of the tasks are located within the project report.

Task	**Section Described**
Tasks 1 and 2: Stream Reconnaissance and Trip Itineraries	Study Area and Methodology. Individual trip itineraries are not included in this report, but were a necessary part of the planning process.
Task 3: Field Work I (Mapping)	Field mapping of the upper 70 miles of the river, from Elmendorf to below Falls City, TX.
Task 4: Data Processing I	Methodology: Channel and Bank Identification
Task 5: Initial analysis	Methodology: Variable Measurement
Task 6: Field Work II	Due to continued rainfall and high water in the lower study reach, this task was modified and completed using remote sensing techniques. This is described in Methodology.
Task 7: Data Processing II	Results: Classification Results: Geomorphic Classification Results: Evaluation
Task 8: Final Analysis	Results: Geomorphic Characterization
Task 9: Report	This document is the report. A set of two DVD-R discs contains an ArcGIS database of the project, including a detailed geomorphic map of the study area and a photographic inventory of geomorphic features.

INTRODUCTION

Water flowing in an open channel is governed by the gradient acting to move the water down slope due to the acceleration of gravity and frictional resistance opposing that movement (Wolman and Miller 1960, Leopold et al. 1964, Knighton 1998, Sturm 2001). The shear stress produced from the interaction of these two forces allows water and sediment load in transport to affect channel boundaries. River morphology is a product of the interaction of fluid flow and erodable boundaries (bed and bank) to create fluvial forms. The interrelation of these fluvial forms at various spatial and temporal scales creates the channel morphology forms and processes in the present (Schumm and Lichty 1965).

Physical habitat is dependent on the structure of the river and its availability to biota for interaction (Southwood 1977). The structure of the river includes channel shape and morphology (Brierley and Fryris 2000), and therefore channel morphology is directly related to physical habitat. The diversity of morphology determines the amount of available physical habitat in a system (Dyer and Thoms 2006). This morphology acts as a template for habitat diversity and availability, and this geomorphic template is a main mechanism for biotic development and ecological processes (Montgomery and Buffington 1997). Geomorphic features form discrete habitats (e.g. pool, riffle, stream confluences) and therefore geomorphic classification can be used as a surrogate for determining habitat characteristics (Brierley and Fryirs 2000).

Texas Senate Bill 2 dictates that an instream flows data collection and evaluation program be implemented in priority basins by the end of 2010. The San Antonio River watershed has been indicated as a priority basin due to issues of water reuse and wastewater return flows. On advisement of the National Academy of Sciences review (National Research Council 2005) of the Texas Instream Flows Program (TIFP) technical overview (2002), consideration of geomorphic character and processes is a necessary and vital part of the TIFP. In order to achieve this goal for the Lower San Antonio River, a process-oriented geomorphic classification scheme is needed. In accordance with the scope of work presented to the Texas Water Development Board (TWDB), I have characterized the geomorphology of the Lower San Antonio River for use by the TIFP according to three specific research objectives:

1. Define geomorphic process reaches for the study area based on measurable variables and a multivariate statistical classification approach.
2. Evaluate the accuracy of the statistical classification method against a manually performed classification using the same variables.
3. Identify and discuss the expected geomorphic characteristics and emergent patterns of each manually classified reach.

This report outlines a classification approach that uses a statistical technique to separate a study area into reaches of geomorphic similarity. A second classification of the same study area is performed throug a combination of field observation, aerial photography, and Light Detection and Ranging (LiDAR) data. The statistical approach is compared to the manual classification to assess its accuracy and evaluate any benefits. Given Senate Bill 2 and the charge to the Texas Water Development Board, Texas Commission on Environmental Quality, and the Texas Parks and Wildlife to determine environmental flow needs for priority basins by 2010, statistical classification of geomorphologic character can present an easy and standardized technique to begin to realize this goal.

STUDY AREA

The study area includes the main stem of the Lower San Antonio River from approximately Elmendorf, Texas to the confluence with the Guadalupe River, about 209 mi. (336 km). This area drains approximately 4,200 mi.^{2} (11,000 km^2), and includes two major tributaries: the Medina River and Cibolo Creek (Figure 1).

Climate

Climate in the study area is semi-arid in the upper basin, becoming more humid downstream as it approaching the Gulf Coast. This spatial trend of increasing humidity downstream in the watershed is reflected in the precipitation record. Annual average rainfall amounts vary from 27.5 in. (~700 mm) in the upper portion of the study area, with averages increasing to 37.5 in. (~950 mm) with increasing proximity to the coast. Precipitation is bimodal, with peaks in May and September (National Oceanic Atmospheric Administration 2006a, 2006b). Wet and dry cycles are apparent when average precipitation is plotted by decade (Figure 2). This trend may be indicative of the El Niño Southern Oscillation (ENSO), in which Pacific Ocean surface water temperatures fluctuate. When the temperatures in the Pacific rise (El Niño), precipitation tends to increases, and when they fall (La Niña) precipitation tends to decreases. According to the precipitation record, the study area is currently in a dry cycle.

Physiographic and Geologic Setting

Surface geology directly impacts soil mineralogy as well as influences valley and channel morphology. The underlying geology in the study area correlates well with the physiographic regions. The San Antonio watershed can be coarsely divided into four physiographic regions. In the upper basin, the Edwards Plateau region dominates with thin, poorly developed soils and exposed upper and lower Cretaceous period (66-146 Ma) limestones (Brown Waechter, and Barnes 1983). Due to the combination of thin soils and steep topography, this physiographic region may produce extreme peak discharges from flood events (Baker 1977). Though the study reach does not include either of these physiographic regions, they influence the flow record and flood history of the study reach (see Flow Analysis).

Southeast of the Balcones Fault Zone is the Blackland Prairie region, with well developed soils and clays several meters thick. Bedrock in this area is typically shale and sandstone deposited during the Tertiary period (1.8-66 Ma) (Proctor et al. 1974). Approximately the first 30 mi. (48 km) of the study reach are in this region. Cuestas mark the transition into the third physiographic region. The Post Oak Savannah, typified by rolling hills oriented parallel to the coastline, covers approximately the middle 70 mi. (113 km) of the study reach. Underlying geology in this region consists of shales and sandstones deposited almost exclusively during the upper Tertiary (Proctor et al. 1974). Downstream of the Cibolo Creek confluence lays the fourth region, the Coastal Plain. Pleistocene Epoch (11,550 BP-1.8 Ma) shale deposits dominate (Aronow et al. 1987). Soils are sandy, topography is minimal and the vegetation consists of mainly shrubs. The remainder of the study reach is contained within this last region.

Anthropic History

Growth and urbanization in the upper part of the basin has had an effect on the flow regime and river morphology. In 1900 the population of the city of San Antonio was 53,321; in 1950 it was 408,442, and in 2000, 1.14 million (Handbook of Texas 2006b). Olmos dam, with a storage of 15,500 ac-ft. (0.019 km^3), was built upstream of downtown San Antonio in 1927 following a devastating flood in 1921 (Handbook of Texas 2006a). This dam controls flows into the downstream river basin including the study reach. Two diversion tunnels at Olmos dam route flood water into an underground tunnel that runs for 3 mi. (4.8 km) and returns the flood water to the San Antonio River downstream of the city proper. On the southeast side of the city, two dams were built on tributaries (Calaveras and Braunig Creeks) of the main stem in 1962 and 1969 respectively. The resultant reservoirs are used to store treated wastewater and serve as cooling lakes for power plants. Discharge from the lakes make up a portion of the San Antonio River's base flow, giving the low flow hydrograph a distinctive sine wave pattern during dry periods.

The major land use in the watershed has changed as the population has grown. During the first half of the 20th Century, the area outside of the city of San Antonio was primarily cotton row cropping (Handbook of Texas 2006a). It has since changed to mainly grazing and grain cropping. The combination of intense row cropping from the Balcones Fault Zone to the coast and urbanization in San Antonio through the 1900s to 1950s has contributed to major geomorphic changes in the main stem river such as loss of the riparian corridor, channel widening, and incision in some places. From the 1950s to present day, continued growth in the city of San Antonio has impacted runoff response and increased peak discharges. The river has over-steepened banks in many parts of the upper study reach and has effectively disconnected itself from the floodplain in many areas.

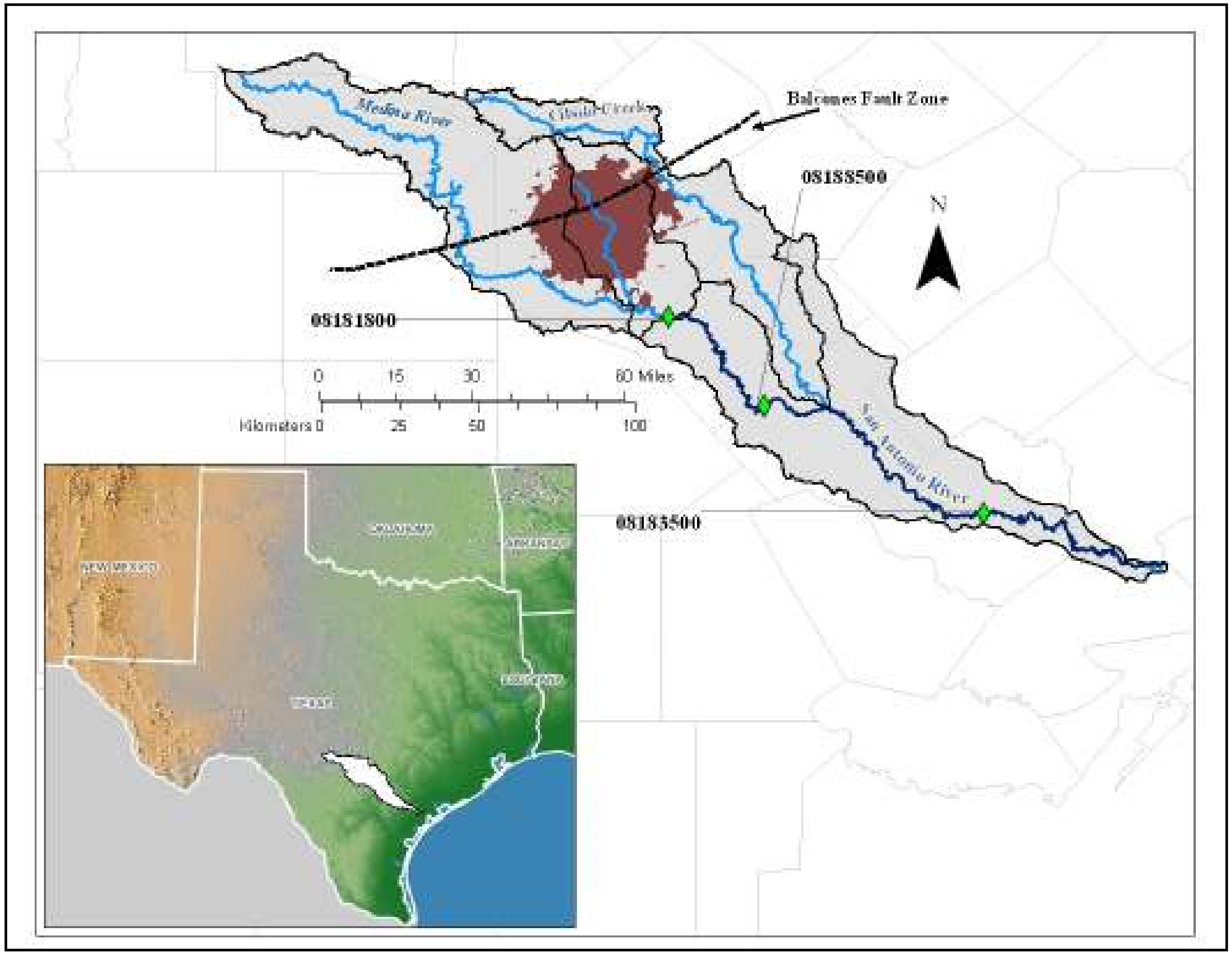

Figure 1. The San Antonio River Watershed. The study reach is indicated as dark blue. There are two perennial tributaries; Cibolo Creek and the Medina River. The three long term USGS stream flow gages are indicated with green diamonds, callouts identify the gage number. The city of San Antonio is indicated in brown. Total watershed area is about 4,200 mi.^{2} (11,000 km^2).

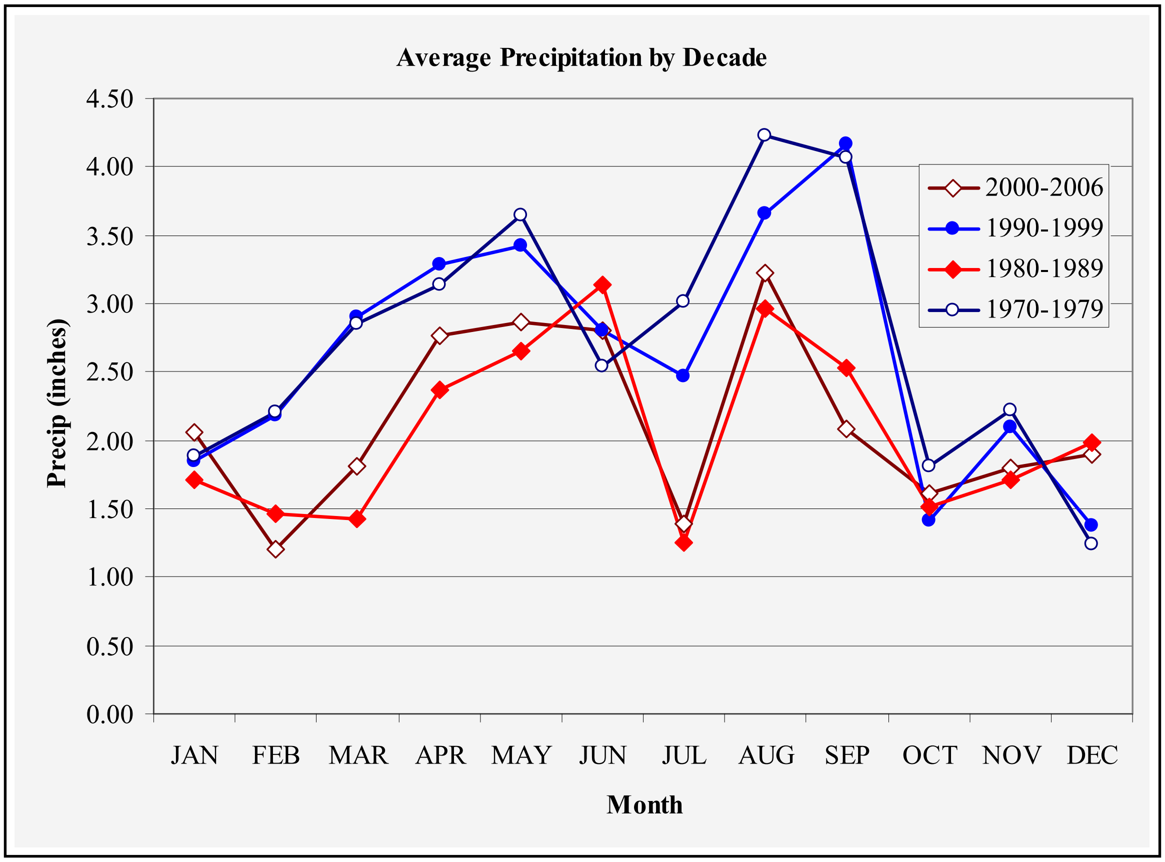

Figure 2. Average precipitation for the San Antonio City station for 1970-2006. Data are plotted by month and broken into decades. The bimodal trend, as well as a wet/dry cycle, is evident in the data. Notice that according to the precipitation record the study area is currently in a dry cycle.

Flow Analysis

Six United States Geological Survey (USGS) stream flow gages occur in the study reach. Table 1 provides details about the gages, including their contributing areas and periods of record. Due to short or incomplete periods of records, only three of the gages were used for analysis purposes (08181800, 08183500, and 08188500). Their locations are indicated as diamonds on Figure 1.

Table 1. USGS gages in the study reach. Asterisks mark those used for analysis.

Gage ID	Name	Area mi.^{2} (km^2)	Period of Record
08181800*	San Antonio Rv nr Elmendorf, TX	1,743 (4,514)	1962-2007
08183000	San Antonio Rv at Calaveras, TX	1,786 (4,626)	1918-1925
08183200	San Antonio Rv nr Floresville, TX	1,961 (5,079)	2006-2007
08183500*	San Antonio Rv nr Falls City, TX	2,113 (5,473)	1925-2007
08188500*	San Antonio Rv at Goliad, TX	3,921 (10,155)	1924-2007
08188570	San Antonio Rv nr McFaddin, TX	4,134 (10,707)	2005-2007

Figure 3, 4, and 5 show flow hydrographs for USGS gages 08181800 (Elmendorf), 08183500 (Falls City), and 08188500 (Goliad) respectively. The hydrographs are color coded to show their "Environmental Flow Components" as computed by the Indicators of Hydrologic Alteration software (IHA) (The Nature Conservancy 2007). IHA classifies each flow into groups based on return period and flow percentile values. Though useful as a reference, the IHA assumes that small floods (2 yr. return period) represent the bankfull flood conditions, which may not be true (Knighton 1998). The hydrographs show that the flow records for the gages in the study reach are typified by multiple high flow pulses, several small floods, and several large floods.

Figure 6 is a storm hydrograph from the June 2004 flood, which is the most recent large flood (indicated in orange). The figure plots the instantaneous discharge values at 15 minute intervals for each gage. The Central Texas region is noted for quick and flashy flow response (Baker 1977), and the record from the Elmendorf gage exemplifies this extremely flashy response. During this flood, discharge at the Elmendorf gage increased from approximately 1,400 cfs (40 cms) to 16,100 cfs (456 cms) in under 22 hours. The flood peak attenuated with travel downstream, and the peaks at both the Falls City and Goliad gages are much lower. The Elmendorf gage is the closest to both the city of San Antonio and the Central Texas region. Seasonal median flows (Figure 7) include a peak in early June that may represent flash flooding from thunderstorms common during the early summer months.

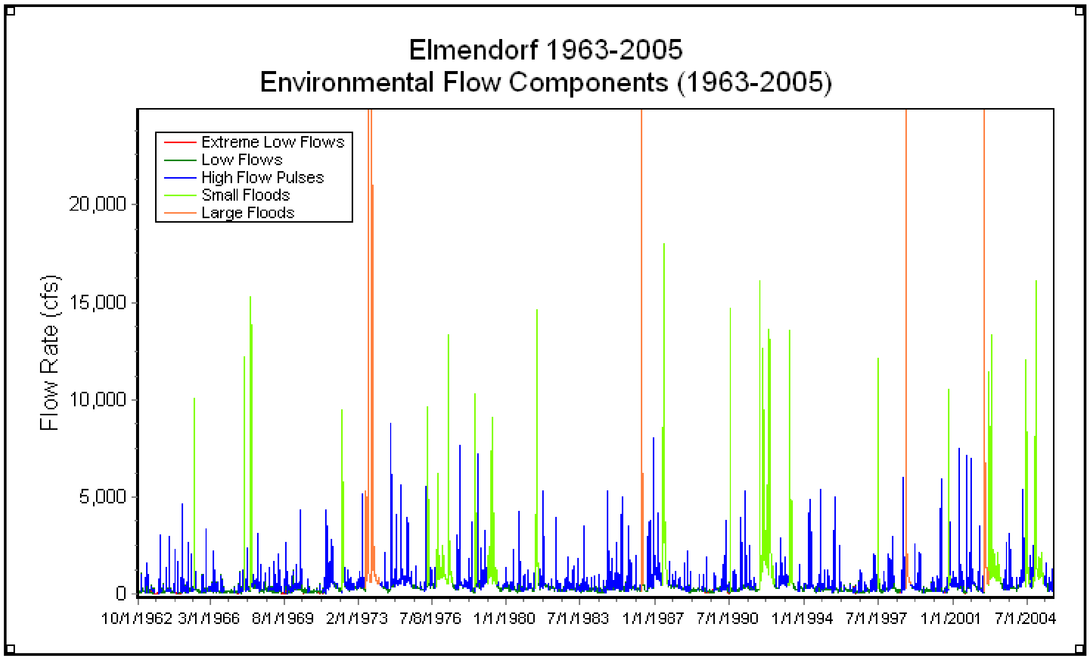

Figure 3. Hydrograph of USGS gage 08181800 (Elmendorf).
Environmental flow components are computed using IHA.

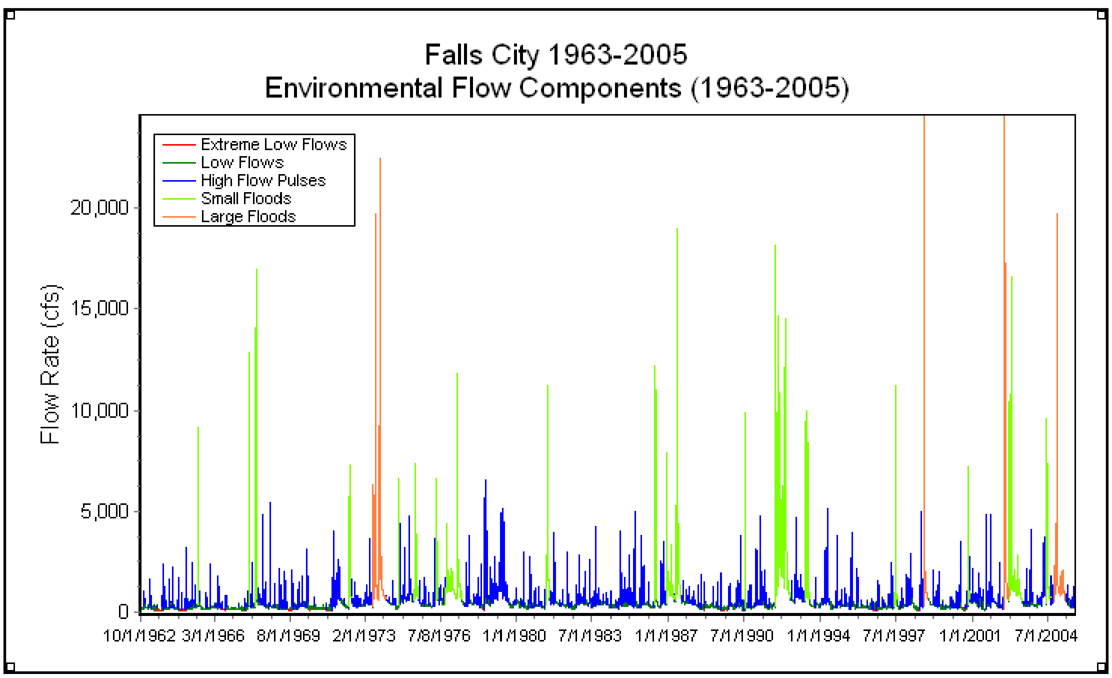

Figure 4. Hydrograph of USGS gage 08183500 (Falls City).
Environmental flow components computed using IHA.

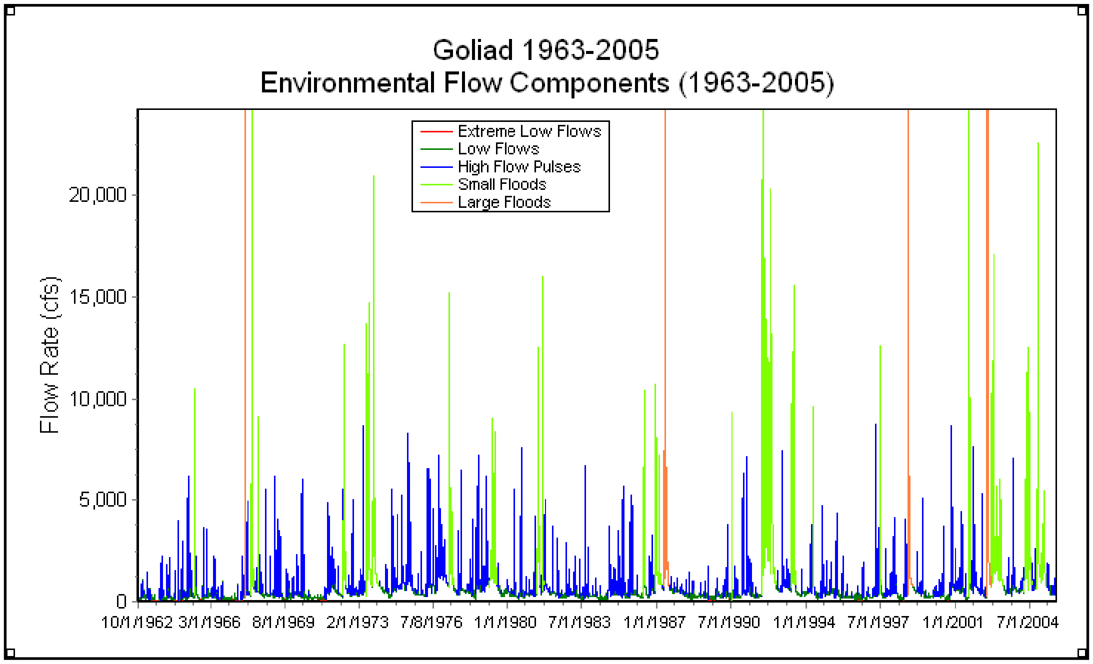

Figure 5. Hydrograph of USGS gage 08188500 (Goliad).
Environmental flow components computed using IHA.

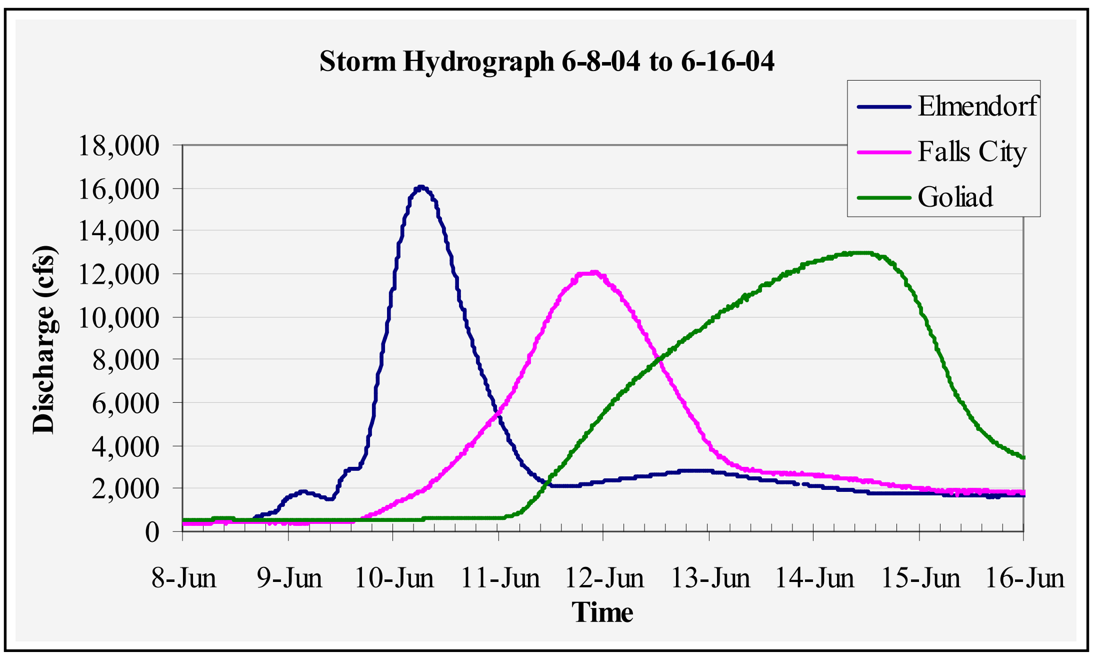

Figure 6. Storm hydrograph of the June 2004 flood. The hydrographs illustrate the flashy flood response of the upper portion of the study reach. Time to peaks are 22, 54, and 82 hours for the Elmendorf, Falls City, and Goliad gages respectively.

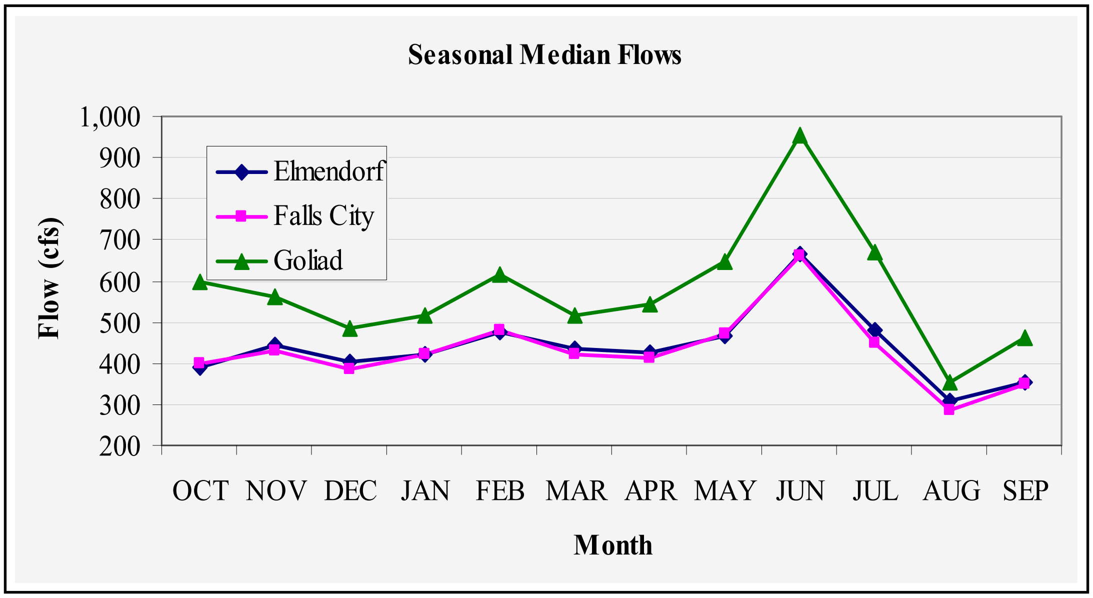

Figure 7. Seasonal median stream flows plotted by month. Notice there is a large peak in early June that may represent flash flooding from common thunderstorms occurring in the study area during the early summer months.

METHODOLGY

The study reach is grouped into distinct geomorphic process reaches. A geomorphic process reach as a contiguous portion of channel with similar geomorphic characteristics and associated processes identified by either the statistical or manual methods described in this chapter.

Data Gathering and Preparation

Base data were collected from several sources to aid in the measurement of watershed parameters including slope, sinuosity, planform, valley setting, and soil characteristics. Table 2 details the data gathered and the associated watershed parameters.

Table 2. Data sources and their purpose of use collected in the study area.
Asterisks designate data used for base map purposes only.

Data	Purpose	Source
2' Contour LiDAR	Centerline, Banks, Valley XS, Feature Identification	San Antonio River Authority (SARA)
3" Arc-Second SRTM DEM	Watershed Delineation, Slope, Valley Setting	USGS Seamless Data Portal
6" Greyscale Ortho-imagery 2004	Centerline, Banks, Feature Identification	San Antonio River Authority (SARA)
1:250,000 US General Soils	Runoff Potential (HSGs)	National Resource Conservation Service
Level IV Ecoregions*	Physiography, Vegetation Trends	Texas Parks and Wildlife
Political Boundaries & Roads*	Location, Base Map	Texas Natural Resources Information System
1 m DOQQ 3 band Imagery 2004 & 1996	Riparian Corridor Vegetation/Land-use, Feature Identification	Texas Natural Resources Information System

Watershed Delineation

Change within a watershed has an impact on the geomorphic character of a given reach (Knighton 1998). Therefore it is necessary to delineate the contributing watershed for the entire study area, as well as for each geomorphic process reach identified by classification. Using Arc Hydro (Maidment 2002) and Geographic Information System (GIS) software, an appropriate watershed outlet was chosen, the watershed delineated, and the contributing watershed area calculated for each point of interest. Arc Hydro tools were also used to determine the Shreve Stream Order (Shreve 1969) for each incoming tributary in the study reach. Stream order is a means to compare the potential flow magnitude for each tributary.

Channel and Bank Identification

The 2004 channel centerline was drawn and used for subsequent analyses and determining geomorphic process reaches. Bank erosion and channel meander migration are estimated from width measurements taken along the channel centerline (Brice 1974, 1982, Legasse et al. 2004). Using aerial photography and LiDAR data from 2004 (SARA), both the centerline and active bank features were digitized using GIS software. The centerline was digitized at a fixed scale of 1:2,500. Banks were digitized at a scale of 1:5,000 and the placement decision was based largely on the LiDAR data. Banks were placed at the first break in slope perpendicular to the river flow and interpreted as the median flow active bank line. Bank placement was later checked against discernable features present in the aerial photography.

Variable Measurement

Valley Slope

Valley slope can be interpreted as an independent channel-shaping control and representation of watershed physiography over temporal scales of 10^1–10^2 years (Schumm and Lichty 1965, Knighton 1998). To measure valley slope, the river centerline was divided into 2 mi. (3.2 km) segments in downstream order. Using 3” arc-second Shuttle Radar and Topography Mission (SRTM) elevation data, the average elevation for each segment was calculated for all cells in a 20 ft. (6 m) radius. Final measurements of valley slope are used as a variable in geomorphic process reach classification.

Sinuosity

Stream sinuosity is the ratio of stream length to straight line length between two points (Knighton 1998). In single thread channels such as the study reach, sinuosity aids in interpretation of suspended sediment carrying capacity, lateral channel stability, and valley confinement (Brice 1974, 1982, Schumm 1977). Using GIS software, the river centerline was divided into one mile segments. Then, using Hawth’s Analysis Tools (Beyer 2004) software, sinuosity values for each one mile segment in the downstream direction were calculated. Sinuosity values are categorized according to the level of sinuosity as defined in Table 3. An average sinuosity value was calculated for each geomorphic process reach, and was used to characterize each geomorphic process reach.

Table 3. Sinuosity categories for river centerline segments. Modified after Brice (1982).

Category	Sinuosity
Straight	1.00 - 1.05
Sinuous	1.06 - 1.25
Meandering	1.26 - 2.00
Torturous	2.01+

Planform Type

The planform of a river describes the lateral pattern of flow in the downstream direction. Planform is a result of channel resistance to flow and therefore can be used as a measure of channel adjustment (Knighton 1998). The assumption that river planform represents channel form adjustment is used to classify rivers based on geomorphology by several researchers (Leopold and Wolman 1957, Brice 1974, Schumm 1977, Rosgen 1996, Legasse et al. 2004, Brierley and Fryirs 2005).

The San Antonio River study reach is a single thread channel with several planform patterns over its length. To capture these pattern changes, each one mile segment is assigned a planform type based on an approach modified from both Brice (1982) and Legasse et al. (2004). Table 4 lists each planform type and its associated process interpretation. Planform types are determined through a three step process. First, the river centerline is evaluated as either single or double phase. Single phase is when the river meanders in a single sinusoidal pattern. Double phase patterns occur when the same sinusoidal meander has a smaller secondary meander pattern superimposed. Second, the centerline is evaluated as either a regular, alternating, or irregular pattern. An alternating pattern is typified by straight channel reaches with short reaches of tight meanders interspersed. Irregular patterns do not conform to alternating or regularly spaced meander bends and exhibit an erratic meander pattern in the floodplain. Third, each meander bend is evaluated for whether the channel bank is wider at the bends than along adjacent straight sections. Each planform characteristic is illustrated in Figure 8.

Table 4. Channel planform types in the Lower San Antonio River.

Planform Type	Description	Process Interpretation
A	Single Phase equal-width	Stable, resistant banks
B	Single Phase wider at bends	Unstable, active migration
C	Dual Phase equal-length	Stable, long-term adjustment
D	Dual Phase wider at bends	Unstable, active migration, adjusting to long-term changes
E	Alternating, straights with tight bends	Active at bends, local factors controlling
F	Straight	Stable, resistant banks, low energy

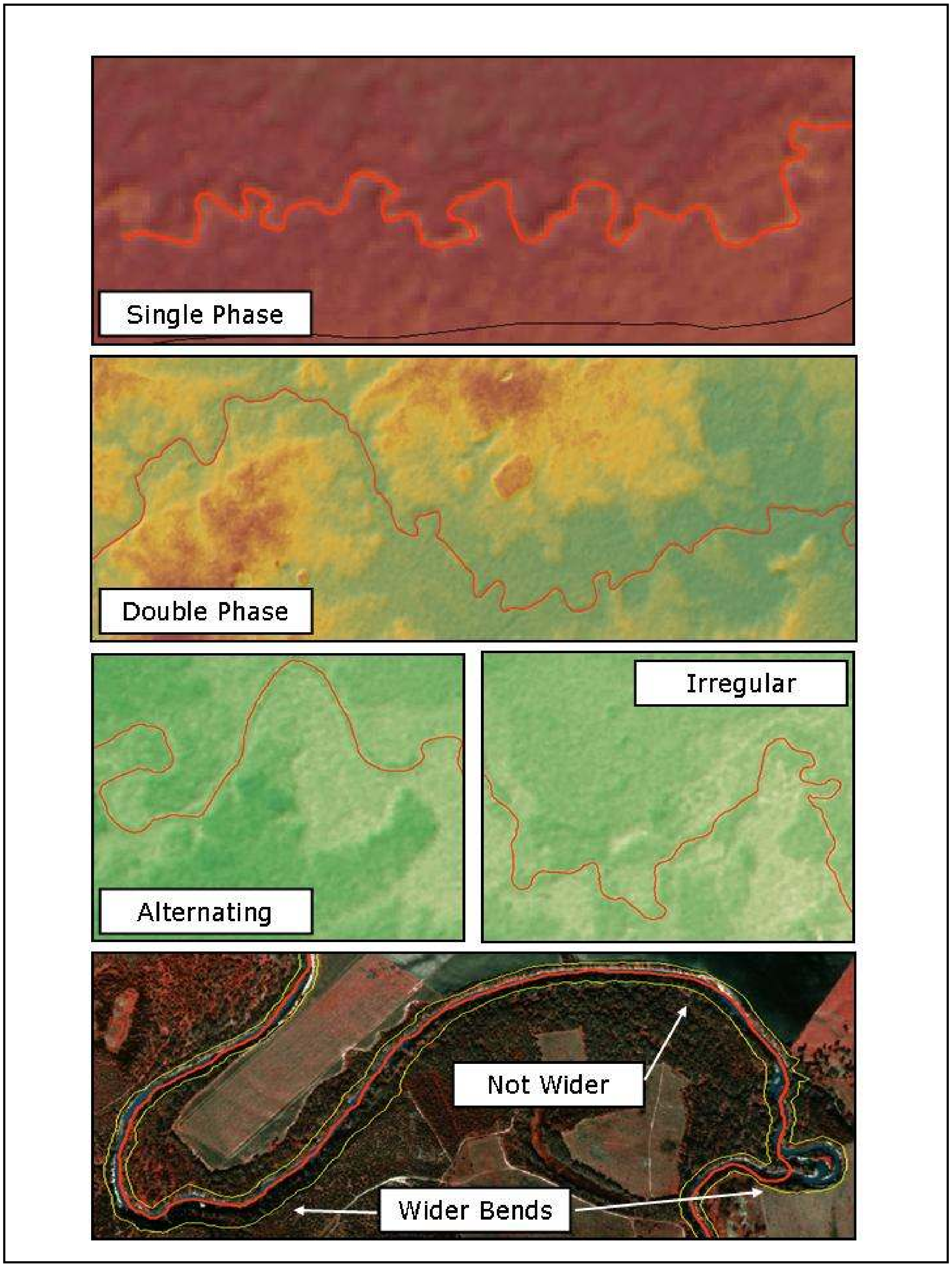

Figure 8. Illustration of planform characteristics. Each tile in the figure shows the characteristics considered in the creation of the Planform variable for the San Antonio River.

Valley Setting

Valley setting is important for evaluating long term channel response and evolution (Brierley and Fryirs 2005). Valley margin placement was determined using breaks in slope perpendicular to stream flow. Aerial photographs were used to adjust this placement where necessary. At approximately 140 mi. (227 km) downstream, as the river approaches the coast, all discernable evidence of a valley margin disappears and the watershed boundary was used as a guide in delineation. A 10-sample suite of valley width values was used to define width percentiles. The valley is identified as narrow if in the lower third percentile, medium if in the middle third percentile, and wide if in the upper third percentile. This value was then assigned to the corresponding channel centerline segment and used in classification.

Soil Groups

Soil properties directly influence the amount and rate of overland flow to the channel (Mockus 1964, Dunne and Leopold 1978). Soil characteristics also influence bank texture and thus affect lateral stability (Thorne 1998). The Natural Resource Conservation Service (formerly the Soil Conservation Service) has classified soils into four Soil Groups based on their infiltration properties (Mockus 1964; Table 5). Often, several soil groups fall within a channel reach. Where this occurs, the dominant soil group is used to characterize that channel reach.

Table 5. SCS Soil Groups. Adapted from Mockus (1964).

Soil Group	Description	Infiltration Rate (mm/h)	Soil Texture
A	Lowest runoff potential. Deep sands with very little silt and clay. Deep, rapidly permeable loess.	8-12	sand, loamy sand, sandy loam
B	Moderately low runoff potential. Sandy soils less deep than A, and loess less deep or less aggregated than A. The group has above-average infiltration after thorough wetting.	4-8	silt loam, loam
C	Moderately high runoff potential. Shallow soils and soils containing considerable clay and colloids, though less than those of group D. Below-average infiltration when saturated.	1-4	sandy clay loam
D	Highest runoff potential. Clays of high swelling percent, and shallow soils with near impermeable sub-horizons.	0-1	clay loam, silty clay loam, sandy clay, silty clay, clay

Classification

Statistical Approach

Statistical clustering algorithms are used to group objects according to multivariate similarities (Kachigan 1991). Most algorithms use an approach where a set of n objects is measured on x variables (Figure 9). For this project, the objects are one-mile segments of the study reach centerline. All objects are compared to create a similarity or distance matrix. The distance matrix is used in an iterative process to create clusters for which there is maximum variability between clusters and minimum variability within each cluster. The results are compared and interpreted by the researcher. For this project, a *k*-means algorithm (MacQueen 1967) is used. In the *k*-means algorithm, the number of clusters (*k*) is determined a priori by the researcher. After the objects are defined, arbitrary centroids are assigned, and each object is assigned to the closest centroid as determined from the distance matrix. Then, *k* new centroids are found based on the initial centroid grouping. In this way, an iterative loop is formed. This loop continues until the centroids no longer change position. The number of clusters is chosen to maximize the cluster variability.

For the Lower San Antonio River, geomorphic process reaches were statistically determined using a clustering algorithm in which the variables are similar to those of Heritage, Charlton, and O'Regan (2001). Clusters are determined using 209 one-mile (336 km) centerline channel segments. The variables used include: valley slope, sinuosity, planform type, valley

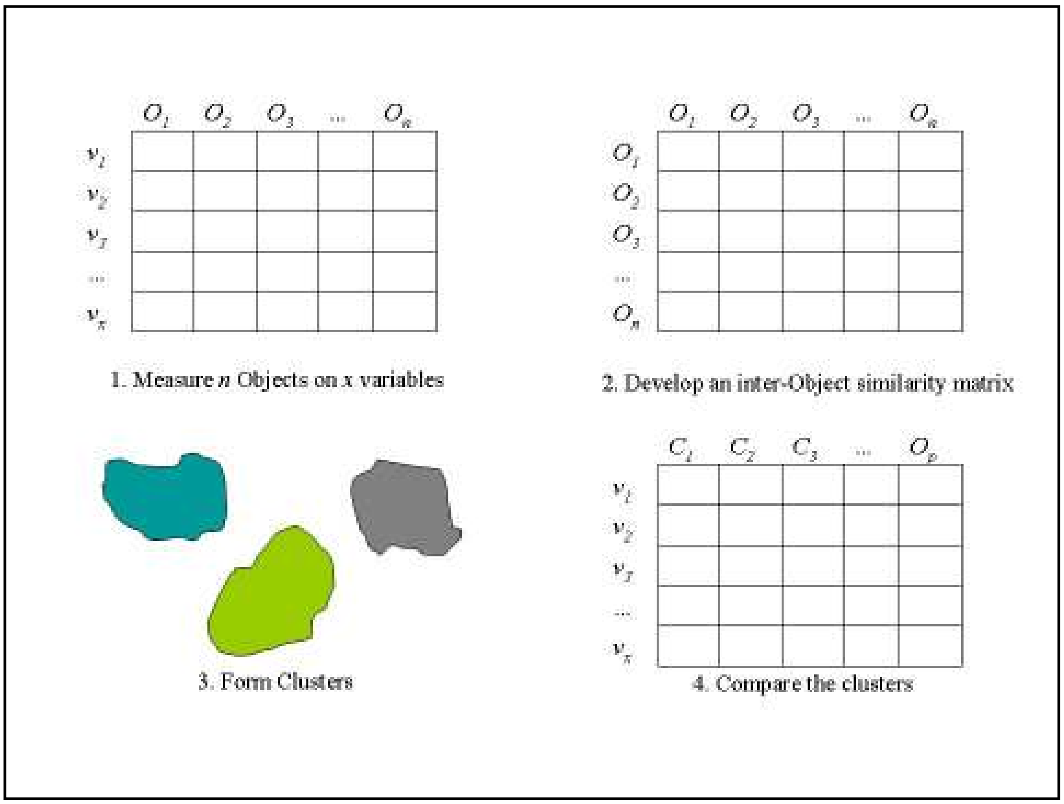

Figure 9. Illustration of a general cluster algorithm approach. There are four steps, with step three being iterative. The goal is to produce cluster groupings which maximize between cluster variability while minimizing intra-cluster variability.

setting, and soil group. Through *k*-means clustering, channel segments were grouped based on similarity in the variables. Several runs of the algorithm were made in two different configurations. For each run, a different number of clusters were chosen, and the results evaluated for significance. The first configuration included all five of the measured variables. In the second configuration, the valley slope and sinuosity variables were removed from analysis because of a lack of variability in channel slope and spatial distinctness in sinuosity. Without variability in slope or sinuosity, the clustering results were deteriorated. The most meaningful results were found using the planform type, valley setting, and soil group variables with $k = 25$

clusters. Each cluster group represents a geomorphic process reach, as it is a contiguous portion of channel with similar geomorphic processes.

Manual Approach

A manual classification was performed over the entire study reach. The general procedure for this approach followed the steps outlined in "Part One: Step One" of the River Styles characterization described by Brierley and Fryirs (2005) with some modifications (Figure 10). Reach boundaries were delineated by comparing the measured variables graphically in GIS software. In order to allow for direct evaluation, only the measured variables and tributary inputs were used to define reach boundaries. The boundaries were first divided based on planform type characteristics, which were adjusted until they visually aligned with the spatial extent of the valley setting, sinuosity, slope, and soil groups. One notable difference between the manual and statistical approach is that in the manual approach, tributary inputs were easily identified and used in defining reach boundaries.

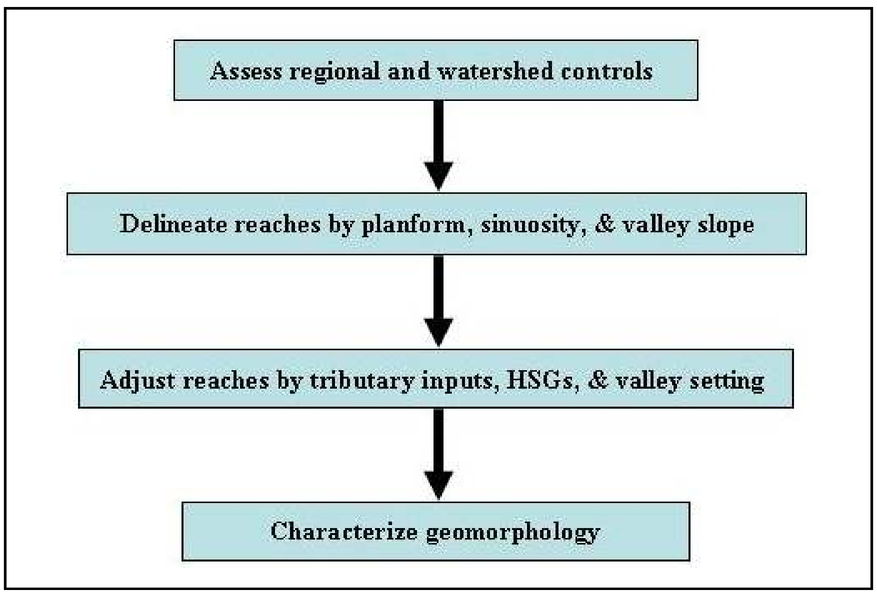

Figure 10. Procedure tree for manual classification approach. Modified from River Styles "Part One: Step One" (Brierley and Fryirs 2005).

<u>Evaluation</u>

To evaluate the effectiveness of the statistical classification approach, the statistically defined geomorphic process reaches are compared segment by segment to the manually defined reaches. Any mismatches between the statistical and manual results are identified and labeled. In some cases, the boundaries of the manual and statistical reaches do not match. In these cases, the manual reach is compared against the cluster reach with the most matching segments, and the outlying cluster groupings are identified as mismatches. Once identification of mismatches is complete, the percent error is calculated as the ratio of the number of mismatches to the total number of segments. Two evaluations of the results were performed. The first comparison was of the unadjusted results, and the second was conducted after adjusting the statistically defined geomorphic process reaches to account for tributary inputs. This was done by assigning a "correctly identified" value to cluster groups which were mismatched due to the inclusion in the manual grouping of a separate reach for tributary inputs. Percent error was then recalculated.

Geomorphic Characterization

Once identified, the geomorphic process reaches were examined in detail to characterize their geomorphic features and processes. The approach for the geomorphic characterization of each reach is based on the "River Styles Performa" described by Brierley and Fryirs (2005). For each reach, a list of common geomorphic units is identified through either field mapping or aerial photography interpretation. These geomorphic units are listed in Table 6 with their associated form-process linkages. Field mapping was conducted using a Trimble XT GPS device. All collected field data were post-processed and imported into an existing GIS database containing watershed characteristics such as river and valley slope, sinuosity, and drainage area. Field mapping was completed for approximately the first 70 mi. (112 km) of the study reach. Weather and continued flooding prevented field excursions into downstream portions of the study reach. In areas where field mapping was not possible, aerial photography interpretation was employed to map and identify geomorphic features. These data form the basis for geomorphic characterization and reach interpretation.

Table 6. Field mapping units and associated processes.

Type	Example Features	Process Linkage
Depositional	point bar, island, levee	sediment storage, stream power indicator, sediment inputs
Erosional	undercut, bench, scour	increased stream power indicator, incision, meander migration
Geometry	width, bank height, depth	hydraulic geometry used to predict change with discharge downstream
Bank Failure	slump, slab, fall	channel widening, transport regime, increased pore water pressures
Large Woody Debris (LWD)	jam, floodplain jam,	channel change, widening
Confluences	confluence bar	sediment input, geometry change
Anthropogenic	bridge, culvert, channelization	increased stream power, scour

RESULTS

Geomorphic Classification

Supervised Statistical Approach

The measured variables were used in a multivariate *k*-means clustering algorithm to group one-mile segments of the study area. The result of this cluster analysis is a set of 30 geomorphic process reaches and 25 individual clusters, each with an associated value for planform type, valley setting, and soil group. Each cluster can occur as one or more geomorphic reaches, but each geomorphic reach consists of only one cluster. Tables 7, 8, and 9 describe the variables that comprise each cluster in the downstream direction from Elmendorf to the confluence with the Guadalupe River. In Tables 10 and 11, sinuosity and reach slope are plotted, although these variables were not used in the final *k*-means cluster analysis. The tables show the number of segments (objects) with an assigned variable category. The dominant variable in each cluster (reach) is variable with the most associated segments.

The geographic extent and location of each reach is illustrated in Figure 11. A detailed segment by segment comparison of the cluster grouping and the measured variables can be found in the geomorphic database on the included DVD-R. Several patterns emerge from the results in each table. An alternating planform pattern followed closely by a single phase widening pattern are the dominant planform types in the study reach (Table 7). The channel has primarily a single phase planform pattern Elmendorf to Floresville, transitioning to double phase and alternating planform patterns from Falls City to approximately Ecleto Creek (Cluster 13). The Refugio County area (Cluster 4) is an area of single phase widening planform, indicating that this reach may be actively migrating.

There is a trend of valley widening with proximity to the coast (Table 8). From the region downstream of Falls City (Cluster 17) to the coastal plain (Cluster 5), the valley alternates in width from medium to wide in a consistent pattern. The soil groups (Table 9) become more sandy (higher infiltration, lower runoff potential) with proximity to the coast, but return to clay and colloids (low infiltration, high runoff potential) at the coast (Cluster 5). There are long stretches of the study reach with multiple soil groups. In many places, the river forms a natural boundary between two soil types.

Channel sinuosity results exhibit considerable spatial variability. Although there is no obvious natural grouping of the channel by sinuosity, some inferences can still be made (Table 10). The study reach is predominately a meandering river (sinuosity of 1.26-2.00) with very few straight segments. The Refugio County reach (Cluster 4) is by far the most torturous reach. There is a weak pattern of torturous and meandering clusters upstream of Poth (Cluster 23). Valley slopes (Table 11) are also variable, but the range of slope throughout the reach is small, making identifying natural spatial patterns in the data difficult. The majority of the study reach has a valley slope range of 0.00021-0.00035, with a weak trend of decreasing valley slope with proximity to the coast.

Table 7. Planform characteristics of each statistically determined cluster. The clusters are organized in downstream order. Totals represent the number of segments classified with that variable included. Where clusters contain more than one variable, the dominant variable is shown in bold. Asterisks indicate clusters that occur in more than one reach.

	Planform					
Geomorphic Process Reaches in Downstream Order	Single Phase Equal Width	Single Phase Widening	Dual Phase Equal Width	Dual Phase Widening	Alternating	Mostly Straight
1	9					
10	4					
14*					11	
18	6					
24*		9				
23		6			1	
20*						
21					8	
19				8		
17				7		
16				2		
15*					14	
13*					19	
12						2
11		**6**				5
9			12			
8			3			
7						
6						
5	9					
22					7	
3				3		
2				16		
4		29				
25						13
Totals	19	50	15	36	60	20

Table 8. Valley setting of each statistically determined cluster. The clusters (reaches) are organized in downstream order. Totals represent the number of segments classified with that variable included. Asterisks indicate clusters that occur in more than one reach.

Geomorphic Process Reaches in Downstream Order	Valley Setting Narrow	Medium	Wide	No Valley
1		9		
10		4		
14*	11			
18	6			
24*		9		
23		6		
20*		8		
21	7			
19	8			
17		7		
16		2		
15*		14		
13*			19	
12			2	
11		5		
9		12		
8			3	
7			6	
6		3		
5				6
22				1
3				3
2				16
4				29
25				13
Totals	32	79	30	68

Table 9. Hydrologic Soil Group of each statistically determined cluster. The clusters are organized in downstream order. Totals represent the number of segments classified with that variable included. Where clusters contain more than one variable, the variables are shown in bold. Asterisks indicate clusters that occur in more than one reach.

	Hydrologic Soil Group		
Geomorphic Process Reaches in Downstream Order	B: Silt Loam	C: Sandy Clay Loam	D: Clays
1		**9**	**9**
10		4	
14*		11	
18		6	
24*		9	
23		**6**	**6**
20*		**8**	**8**
21		6	**7**
19			8
17			7
16		2	2
15*	**14**	**14**	
13*	**19**	**19**	
12	**2**	**2**	
11	**5**	**5**	
9	**12**	**12**	
8	**3**	**3**	
7	**6**	**6**	
6		3	
5		6	
22		1	
3		3	
2			16
4			29
25			13
Totals	61	135	105

Table 10. Sinuosity category of each statistically determined cluster. The clusters are organized in downstream order. Totals represent the number of segments classified with that variable included. Where clusters contain more than one variable, the dominant variable is shown in bold. Asterisks indicate clusters that occur in more than one reach.

	Sinuosity Category			
Geomorphic Process Reaches in Downstream Order	Straight	Sinuous	Meandering	Torturous
1			**7**	2
10				1
14*		2	**7**	2
18		1	**4**	1
24*			**5**	4
23			2	**4**
20*		3	**5**	
21	1	**3**	**3**	
19	1	**4**	3	
17		2	**3**	2
16	1	1		
15*		5	**8**	1
13*		**8**	7	4
12		1	1	
11	**2**	**2**		1
9	1	**10**	1	
8		3		
7			3	3
6		1	2	
5	1	2	**3**	
22			1	
3	**2**	1		
2	1	**10**	4	1
4		1	8	**20**
25	1	**8**	4	
Totals	11	68	81	46

Table 11. Reach slope of each statistically determined cluster. The clusters are organized in downstream order. Totals represent the number of segments classified with that variable included. Where clusters contain more than one variable, the dominant variable is shown in bold. Asterisks indicate clusters that occur in more than one reach.

	Reach Slope				
Geomorphic Process Reaches in Downstream Order	0.00001-0.00020	0.00021-0.00035	0.00036-0.00050	0.00051-0.00070	>0.00070
1			9		
10			4		
14*			**7**	4	
18				6	
24*		**8**		1	
23				6	
20*	**5**	3			
21			7		
19				8	
17		7			
16					2
15*	4	**10**			
13*	7	**12**			
12	2				
11				5	
9			12		
8	3				
7				6	
6		3			
5				6	
22		1			
3					3
2		16			
4		29			
25				13	
Totals	21	89	39	55	5

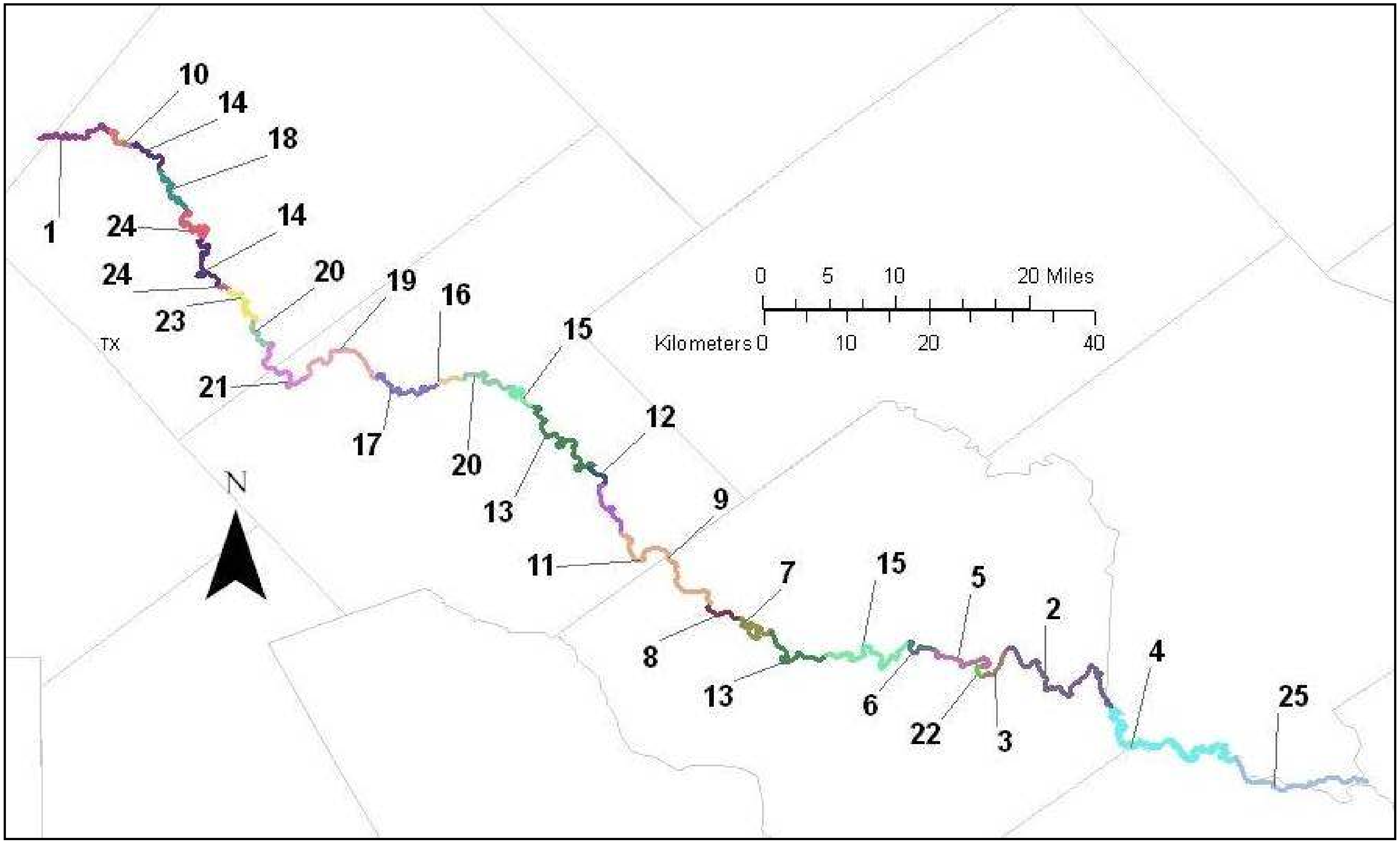

Figure 11. Map of cluster results. The cluster number is identified for each reach. Notice that some clusters occur more than once in the study area.

Manual Approach

The study area was divided into geomorphic process reaches manually using as guides the channel planform, valley setting, soil group, channel sinuosity, and reach slope. This approach yielded 25 distinct geomorphic process reaches. Each reach is named and characterized based on observable geomorphic features. Tables 12, 13, 14, 15, and 16 describe each manually delineated reach. The number of segments within which each variable is active has been tabulated in the same manner as for the statistical cluster analysis. The geographic extent and location of each reach is illustrated in Figure 12.

In an indication of the similarity between the statistical clustering approach and the manual approach, the segment totals for each measured variable in the manual approach (as shown in Tables 12-16) are almost identical when compared to the statistical approach (Tables 7-11). The same general trends from the statistical cluster results are also present in the manual cluster results. The difference between the two approaches is most evident when comparing the geographical distribution of clusters and reaches (Figures 11 and 12).

Geomorphic reaches upstream of approximately Falls City (Reach 19 in Figure 11; Reach 10 in Figure 12) are longer in the manual approach. There are only 9 manually delineated reaches upstream of Falls City while there are 11 reaches in the same area when defined statistically. This difference between the manual and statistical results may be due to highly complex and varied river conditions in this portion of the study area. Conversely, reaches downstream of the Goliad Sandy Clay reach (approximately Reach 22 in Figure 11; Reach 20 in Figure 12) are shorter in the manual approach. There are 5 reaches delineated downstream of Reach 20 in the manual approach (Figure 12), however there are only 4 reaches delineated in the statistical approach, with one of those (Reach 3) being only 3 mi. (4.8 km) long. This difference is a result of the inclusion of tributaries as potential reach boundaries in the manual approach.

Table 12. Planform characteristics of each manually delineated reach. The clusters are organized in downstream order. Totals represent the number of segments classified with that variable included. Where clusters contain more than one variable, the dominant variable is shown in bold.

	Planform					
Geomorphic Process Reaches in Downstream Order	Single Phase Equal Width	Single Phase Widening	Dual Phase Equal Width	Dual Phase Widening	Alternating	Mostly Straight
1	9					
2	4					
3					4	
4	6					
5		8				
6					7	
7		7				
8					6	
9					4	
10				5		
11				3		
12				5		
13				4	1	
14					15	
15					5	**7**
16			1			
17			14			
18		6			**7**	
19					13	
20				4	**6**	
21				15		
22		8				
23		20				
24		1				**7**
25						6
Totals	19	50	15	36	60	20

Table 13. Valley setting of each manually delineated reach. The clusters are organized in downstream order. Totals represent the number of segments classified with that variable included. Where clusters contain more than one variable, the dominant variable is shown in bold.

Geomorphic Process Reaches in Downstream Order	Valley Setting Narrow	Medium	Wide	No Valley
1		9		
2		4		
3	4			
4	6			
5		8		
6	7			
7		7		
8	3	3		
9	4			
10	5			
11	3			
12		5		
13		5		
14		**8**	7	
15			5	
16		**6**	2	
17		**11**	3	
18			13	
19		13		
20				11
21				15
22				8
23				20
24				8
25				6
Totals	32	79	30	68

Table 14. Soil Group of each manually delineated reach. The clusters are organized in downstream order. Totals represent the number of segments classified with that variable included. Where clusters contain more than one variable, the dominant variable is shown in bold.

	Soil Group		
Geomorphic Process Reaches in Downstream Order	B: Silt Loam	C: Sandy Clay Loam	D: Clays
1		9	9
2		4	
3		4	
4		6	
5		8	
6		7	
7		**7**	6
8		6	6
9		3	4
10			5
11			3
12			5
13		3	**5**
14	11	**15**	4
15	5	5	
16	8	8	
17	14	14	
18	13	13	
19	10	**13**	
20		10	1
21			15
22			8
23			20
24			8
25			6
Totals	61	137	105

Table 15. Sinuosity category of each manually delineated reach. The clusters are organized in downstream order. Totals represent the number of segments classified with that variable included. Where clusters contain more than one variable, the dominant variable is shown in bold.

Geomorphic Process Reaches in Downstream Order	Sinuosity Straight	Sinuous	Meandering	Torturous
1			**7**	2
2			**3**	1
3		2	2	
4		1	**4**	1
5			4	4
6			**5**	2
7			3	**4**
8		**4**	2	
9	1	1	**2**	
10		**3**	2	
11	1	1	1	
12		1	**3**	1
13	1	**2**	1	1
14		5	**8**	2
15		1	**3**	1
16	2	**4**	1	1
17	1	**12**	1	
18		4	**5**	4
19		5	**7**	1
20	3	**4**	**4**	
21	1	**9**	4	1
22			3	**5**
23		1	4	**15**
24		**6**	2	
25	1	2	**3**	
Totals	11	68	84	46

Table 16. Reach slope type of each manually delineated reach. The clusters are organized in downstream order. Totals represent the number of segments classified with that variable included.

Geomorphic Process Reaches in Downstream Order	Reach Slope 0.00001-0.00020	0.00021-0.00035	0.00036-0.00050	0.00051-0.00070	>0.00070
1				8	
2	5				
3	4				
4				6	
5		8			
6		7			
7					7
8		6			
9		4			
10				5	
11					3
12				5	
13				4	
14		16			
15	5				
16				8	
17			14		
18		12			
19			14		
20	11				
21		15			
22		8			
23		20			
24				8	
25			6		
Totals	25	97	34	44	10

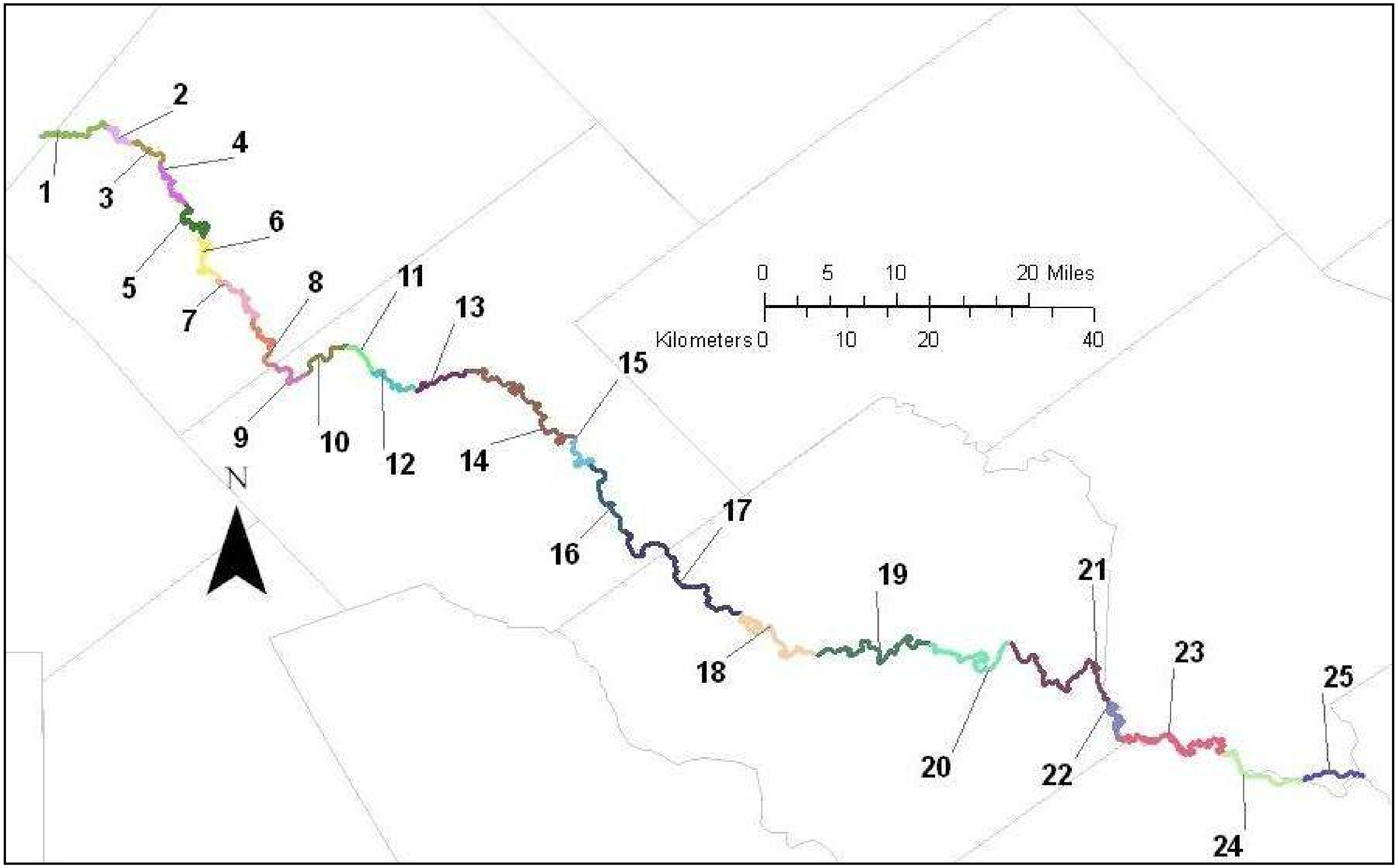

Figure 12. Map of manual classification results. Each reach is identified by a number progressing downstream.

Evaluation

Comparing the statistical approach directly against the manual grouping provides an indication of how well the statistical approach was able to identify meaningful geomorphic reaches based on the measured variables. Using the statistical clustering procedure, 25 significant clusters were formed and 30 separate geomorphic process reaches identified. By coincidence, 25 geomorphic reaches were identified using the manual grouping procedure. However, reach boundaries did not always coincide between the manual and statistical cluster results.

Two runs of the statistical cluster analysis are compared to the manual analysis: one including the measured sinuosity variable, and one omitting the sinuosity variable. Table 17 shows the number of incorrectly identified segments and the total percentage of error between the statistical and manual groupings. An error analysis is given for the cluster analysis adjusted for the presence of tributary inputs. A segment by segment comparison of the cluster grouping and the measured variables can be found in the geomorphic database on the included DVD-R.

Table 17. Error analysis of geomorphic reach identification.

	Clusters w/ Sinuosity	Clusters w/o Sinuosity	Tributary Adjusted
No. of Errors	98	49	27
Percent Error	47.1%	23.6%	13.0%

The inclusion of the sinuosity category had the effect of deteriorating the effectiveness of the clustering algorithm. Though the cluster grouping including sinuosity followed the same general trends as the manual grouping, irregularity of the meander bends and segment locations within those bends generated a percent error equal to almost half the sample (47.1% error). The majority of this error was due to the algorithm classifying something as distinct that was not present in the manual approach. The clustering run excluding the sinuosity variable yielded results with a total percent error of about one quarter of the sample (23.6% error). The majority of these errors occurred when the algorithm classified segments differently than the manual approach. The presence of tributaries in the study reach was not accounted for in the variables used in either clustering approach. For the manual approach, this was not an issue because the researcher includes the tributaries when delineating geomorphic reaches. However, for the statistically defined clusters, there was no direct measurement that accounted for the input of tributaries. This situation is responsible for much of the error in the statistical results. When the output from the second clustering run is adjusted for tributary inputs, the percent error decreases to 13.0%.

Geomorphic Characterization

Each geomorphic process reach from the manual classification is characterized in terms of its geomorphology and observable features. A combination of field mapping and aerial photography interpretation with the aid of LiDAR data was used to determine typical channel and floodplain features. Descriptions of each geomorphic process reach on the Lower San Antonio River are presented in four tables. Table 18 details the reach length, distance from the river mouth, and contributing drainage area of each geomorphic process reach. Table 19 lists each geomorphic process reach with its associated average valley slope and sinuosity. Table 20 identifies the dominant variables defining reach boundaries. Table 21 contains a geomorphic description of each reach along with examples of common channel and floodplain features. The geomorphic database DVD-R included with this report contains a complete photographic inventory of geomorphic character from field mapping excursions for the first 70 mi. (112 km) of the study reach.

Table 18. Geomorphic process reach summary.

Reach	Reach Name	Distance from Mouth mi. (km)	Total Length mi. (km)	Drainage Area mi.^{2} (km^2)
1	Elmendorf Clay Meandering	209 (336)	9 (14)	1,740 (4,506)
2	Elmendorf Sandy Clay	200 (322)	4 (6)	1,846 (4,780)
3	Floresville Partly Confined	196 (316)	4 (6)	1,885 (4,881)
4	Floresville Clay	192 (309)	6 (10)	1,903 (4,929)
5	Floresville Sand	186 (299)	8 (13)	1,958 (5,071)
6	Picosa Creek Sand	178 (287)	7 (11)	2,024 (5,242)
7	Poth Active Clay	171 (275)	7 (11)	2,038 (5,279)
8	Poth Clay	164 (264)	6 (10)	2,070 (5,359)
9	Falls City Confined	158 (254)	4 (6)	2,105 (5,452)
10	Falls City	154 (248)	5 (8)	2,145 (5,556)
11	Marcelina Creek Clay	149 (240)	3 (5)	2,231 (5,777)
12	Karnes City Active Clay	146 (235)	5 (8)	2,239 (5,798)
13	Cow Creek Sandy Clay	141 (227)	5 (8)	2,268 (5,874)
14	Cibolo Creek Confluence	136 (219)	15 (24)	3,131 (8,109)
15	Cibolo Creek Active Sand	121 (195)	5 (8)	3,437 (8,902)
16	Kenedy Meandering	116 (187)	8 (13)	3,559 (9,219)
17	Hondo Creek Sand	108 (174)	14 (23)	3,640 (9,427)
18	Charco Creek Meandering	94 (151)	13 (21)	3,709 (9,607)
19	Goliad Sand	81 (130)	13 (21)	3,862 (10,002)
20	Goliad Sandy Clay	68 (110)	11 (18)	3,897 (10,094)
21	Manahuilla Creek Clay	57 (92)	15 (24)	4,035 (10,450)
22	Refugio Clay	42 (68)	8 (13)	4,080 (10,567)
23	McFaddin Avulsion	34 (55)	20 (32)	4,093 (10,600)
24	Cross Bayou	14 (23)	8 (13)	4,125 (10,683)
25	Elm Bayou	6 (10)	6 (10)	4,144 (10,733)

Table 19. Geomorphic process reach variables.

Reach	Reach Name	Planform Type	Valley Setting	Soil Group	Average Segment Sinuosity	Avg. Valley Slope
1	Elmendorf Clay Meandering	A	Medium	C/D	1.84	<0.00001
2	Elmendorf Sandy Clay	A	Medium	C	2.24	0.00077
3	Floresville Partly Confined	E	Narrow	C	1.61	<0.00001
4	Floresville Clay	A	Narrow	C	1.65	0.00041
5	Floresville Sand	B	Medium	C	3.16	0.00037
6	Picosa Creek Sand	E	Narrow	C	1.92	0.00024
7	Poth Active Clay	B	Medium	C/D	2.02	0.00039
8	Poth Clay	E	Medium	C/D	1.56	0.00098
9	Falls City Confined	E	Narrow	C/D	1.77	0.00012
10	Falls City	D	Narrow	D	1.46	0.00055
11	Marcelina Creek Clay	D	Narrow	D	1.11	0.00068
12	Karnes City Active Clay	D	Medium	D	1.61	0.00012
13	Cow Creek Sandy Clay	D	Medium	C/D	1.33	0.00056
14	Cibolo Creek Confluence	E	Medium/Wide	B/C	1.78	0.00026
15	Cibolo Creek Active Sand	E	Wide	B/C	2.24	0.00093
16	Kenedy Meandering	E	Medium	B/C	1.32	0.00022
17	Hondo Creek Sand	C	Medium	B/C	1.49	0.00003
18	Charco Creek Meandering	E/B	Wide	B/C	2.07	0.00075
19	Goliad Sand	E	Medium	B/C	1.77	<0.00001
20	Goliad Sandy Clay	D	No Valley	C	2.00	0.00076
21	Manahuilla Creek Clay	D	No Valley	D	1.96	0.00001
22	Refugio Clay	B	No Valley	D	2.62	<0.00001
23	McFaddin Avulsion	B	No Valley	D	3.03	0.00018
24	Cross Bayou	F	No Valley	D	1.32	0.00071
25	Elm Bayou	F	No Valley	D	1.36	0.00094

Table 20. Dominant variables defining reach boundaries.

Reach	Reach Name	Boundary Controls
1	Elmendorf Clay Meandering	Slope, Sinuosity, Soil Group
2	Elmendorf Sandy Clay	Slope Sinuosity, Soil Group
3	Floresville Partly Confined	Planform, Valley, Sinuosity, Slope
4	Floresville Clay	Planform
5	Floresville Sand	Planform, Valley, Sinuosity
6	Picosa Creek Sand	Planform, Valley, Sinuosity
7	Poth Active Clay	Planform, Valley, Soil Group, Sinuosity
8	Poth Clay	Planform, Sinuosity, Slope
9	Falls City Confined	Valley, Slope
10	Falls City	Planform, Soil Group, Slope
11	Marcelina Creek Clay	Sinuosity, Slope
12	Karnes City Active Clay	Valley, Sinuosity, Slope
13	Cow Creek Sandy Clay	Soil Group, Slope
14	Cibolo Creek Confluence	Planform, Valley, Soil Group
15	Cibolo Creek Active Sand	Valley, Sinuosity, Slope
16	Kenedy Meandering	Valley, Sinuosity, Slope
17	Hondo Creek Sand	Planform, Slope
18	Charco Creek Meandering	Planform, Valley, Sinuosity, Slope
19	Goliad Sand	Planform, Valley, Sinuosity, Slope
20	Goliad Sandy Clay	Planform, Valley, Soil Group, Slope
21	Manahuilla Creek Clay	Soil Group, Slope
22	Refugio Clay	Planform, Sinuosity
23	McFaddin Avulsion	Sinuosity, Slope
24	Cross Bayou	Planform, Sinuosity, Slope
25	Elm Bayou	Slope

Table 21. Geomorphic process reach descriptions and features.

ID	Reach Name	Geomorphic Description	Channel Units	Floodplain Units
1	Elmendorf Clay Meandering	Small but tight meanders with over steepened banks are typical. Bank material is mostly cohesive, though in several places a cobble sized paleo-flood deposit intersects the thalweg creating riffles and gravel bars. Extensive mass wasting is present at meander bends.	Bank slumps, undercut banks, full channel LWD jams, cobble riffles, gravel bars	Slumped banks, scattered meander scars, terrace slumps
2	Elmendorf Sandy Clay	Sinuosity increases in this reach compared to the last reach as the bank material becomes more silty/sandy. Several large mass failures indicate channel widening at large flows. Sand point bars and islands indicate a depositional environment.	Bank slumps, point bars, islands, full channel LWD jams	Slumped banks, scattered meander scars, high flow channels at tight bends
3	Floresville Partly Confined	Sandstone outcrops define the channel planform, creating a distinct pattern of long straight sections followed by short, tight meander bends. Erosion at the tight bends has led to several large tree falls, leading to a high frequency of LWD jams. The terrace is very close to the active channel.	Sandstone outcrops, full channel LWD jams, slab and slump failures	Terrace/channel interfacings
4	Floresville Clay	Isolated bedrock outcrops. Channel sinuosity and cohesive banks create opportunities for mass wasting and failures at both median and higher flows.	Bank slumps, LWD jams, mass failure remnants in channel	Terrace/channel interfacings, scattered meander scars, built levees
5	Floresville Sand	This reach intersects the Queens Sand geologic unit. Steep point bars and undercut banks occur at almost every bend. Very high sinuosity and a medium valley indicate that high mobility. Numerous meander scars are present. There are several high flow channels. Levees have been built between close bends to prevent meander cutoffs.	Steep sand point bars, undercut banks, isolated bedrock outcrops	Numerous meander scars, high flow channels, oxbow lakes, built levees

ID	Reach Name	Geomorphic Description	Channel Units	Floodplain Units
6	Picosa Creek Sand	The confluence of Picosa Creek occurs in this reach. Channel sinuosity is low, and there is an alternating pattern of longer straight lengths with tight meander bends containing point bars and undercut banks.	Undercut banks, occasional LWD jams, small slumps	Isolated meander scaring, steep terrace walls with slumping common
7	Poth Active Clay	This reach is dominated by mass wasting processes, although scattered sand point bars are present. Several tree falls and bank slumps, in conjunction with widening meander bends, indicate that this reach is active. Several large orchards and open fields directly abut the channel. The riparian zone has been removed and gully formation and large scale slumping is common.	Bank slumps, older bank slab failures, tree fall	Steep terraces with older slumped banks
8	Poth Clay	Over-steepened cohesive banks, large bank slumps, gully erosion, LWD jams, and bank failures are common. In the upper portion of the reach, meander scars are common, with many artificially deepened for irrigation purposes. A few of the larger gullies/small tributaries have been dammed.	Tree fall, LWD jams	Meander scars, man made tanks
9	Falls City Confined	The channel is bedrock with sandy clay banks. A large island complex about 3 mi. (4.8 km) into the reach has a small waterfall. Bank widening occurs by bank erosion and failure. Flood terraces are very close to, or interface with the channel.	Undercut banks, complex islands, riffles, boulder bars	Gullies, isolated meander scars, terrace/channel interfacings
10	Falls City	The channel bed is bedrock with sandy clay banks. A large island complex is accompanied by 6 ft. (1.8 m) falls. Bank widening occurs by bank erosion and failure. The valley, though still classified as narrow, widens considerably.	Undercut banks, complex islands, riffles, boulder bars	Gullies, isolated meander scars

ID	Reach Name	Geomorphic Description	Channel Units	Floodplain Units
11	Marcelina Creek Clay	This reach is bedrock with cohesive bank materials. Over steepened banks and a wide channel create only a few LWD jams. Where the riparian vegetation has been removed, large mass wasting and gully processes widen the active channel. Steep banks keep the floodplain disconnected at 100+ year floods.	Bank slumps, over steepened banks	Gullies, scattered terrace slumps
12	Karnes City Active Clay	Very steep and high (~ 40 ft. (12 m)) banks in conjunction with a narrow channel (~60 ft. (18 m)) are typical. Almost every meander bend shows signs of active widening processes through large slump features and bank failures. Medium sized LWD jams occur frequently, though not with the regularity of the Elmendorf reaches. Terraces are present on the insides of bends, usually within 500 ft. (150 m) of the active channel. The outsides of bends have steep banks that abut the terrace directly.	Slumps, steep active banks, LWD jams	Terraces on insides of bends, terrace/channel interfacings
13	Cow Creek Sandy Clay	Steep, tall, and widening banks are common, though a move into sandy clay has changed the processes that cause the widening. Some scattered point bars are present, and the outsides of bends show both undercut erosional features and mass wasting failure features. Numerous meander scars and 3 oxbow lakes indicate a history of channel migration and adjustment.	Scattered point bars, bank slumps, undercut banks	Meander scars, oxbow lakes, gullies
14	Cibolo Creek Confluence	The confluence of Cibolo Creek occurs and marks the transition into the coastal plain and sandier substrate. Point bars and undercut banks are present in the tighter bends, with slumping and gully erosion common in the straight reaches. As the valley widens, the river meander belt width increases, and the terraces become less pronounced. Steep banks separate the active channel from the floodplain.	Point bars, undercut banks, scattered LWD jams, gullies, slumps	Scattered meander scars

ID	Reach Name	Geomorphic Description	Channel Units	Floodplain Units
15	Cibolo Creek Active Sand	The substrate transitions into sand, and the channel is actively migrating. Several meander scars and chutes are present. The valley widens considerably with the transition into the coastal plain region. Heavily undercut banks and gullies occur in every tight bend. There are two oxbow lakes and a stream capture is likely as the reach migrates towards Ecelto Creek.	Undercut banks, point bars, gullies	Meander scars, oxbow lakes, stream capture
16	Kenedy Meandering	The substrate is sandy and the reach is very straight with only a few tight bends (Planform Type is Alternating). Channel banks are steep and tall (>30 ft. (9 m)) with gullies throughout. An occasional point bar and some lateral bars occur, though there is little variability in this reach. Terraces are prominent, and abut the channel except in the few tight bends. This reach marks a transition to a more stable condition downstream.	Gullies, scattered point bars, occasional lateral bars, tree fall	Steep terraces, older gullies
17	Hondo Creek Sand	A very low slope indicates that migration is the main process of channel adjustment. Several large pre-anthropic meander scars cross the valley. Point bars are in almost every bend, especially the tight bends. The banks are steep, but not as tall as reaches upstream (< 30 ft. (9 m)). Complex series of lateral bars, mid-channel sand bars, and islands occur in several places. The channel is narrow (~60 ft. (18m)) but widens (~100 ft. (30m)) where lateral bars are present.	Point bars, lateral/alternating bars, mid-channel bars, isolated islands	Numerous meander scars, oxbow lakes
18	Charco Creek Meandering	Migration is the main process of channel adjustment. Point bars are located in almost every bend. The banks are steep, and complex series of lateral bars, mid-channel sand bars, and islands occur in several places. High-flow channels have formed at very tight bends. Some levees have been built to avoid meander cutoff. Active bank widening features are visible on aerial photography.	Point bars, lateral bars, mid-channel bars, undercut banks	Numerous meander scars, chutes, built levees

ID	Reach Name	Geomorphic Description	Channel Units	Floodplain Units
19	Goliad Sand	Long straight reaches that run perpendicular to the valley, with moderate to tight bends typify this sandy reach. Numerous oxbow lakes and scroll/meander scaring show a history of meander migration. Point bars and undercut banks are typical, and the channel is narrow (< 70 ft wide). There are several small to medium LWD jams.	Point bars, undercut banks, LWD jams	Meander/scroll scars, oxbow lakes, gullies
20	Goliad Sandy Clay	A transition into cohesive material indicates this reach is dominated by mass wasting processes. Scattered point bars are present but small and infrequent. Over steepened banks and slumping are common on the outsides of bends. The valley becomes indistinguishable, and old meander scars are throughout.	Bank slumps, scattered point bars, LWD jams	Meander scars
21	Manahuilla Creek Clay	Cohesive materials line this reach. Isolated point bars are present but rare. Over steepened banks and slumping are common. Meander scars and oxbow swamps indicate past reach mobility. A narrow channel (~70 ft. (21 m)) and brushy banks allow for several small LWD jams.	Bank slumps, scattered point bars, LWD jams	Meander scars
22	Refugio Clay	This reach is marked by a torturous meander pattern and low channel slope. The river transitions to bayou and swamp as it approaches the coast. Mass wasting processes are visible, but very thick brushy vegetation make identification difficult. Several meander scars are present, and most are heavily vegetated swamps or lakes.	Bank slumps, backwater side channels	Meander scars, oxbow lakes and swamps
23	McFaddin Avulsion	This reach is a distributary bayou network. The upper reach is marked by a channel avulsion. The old channel remains slightly connected to the new channel by a network of distributaries. Some slump features are identifiable, though the channel banks are thick with swampy brush. Several small backwater channels are present.	Bank slumps, backwater side channels	Channel avulsion, oxbow lakes and swamps

ID	Reach Name	Geomorphic Description	Channel Units	Floodplain Units
24	Cross Bayou	A true bayou environment, several backwater swamps abut the channel. Distributaries are common t. Land use is mostly rice farming with irrigation water from the channel.	Backwater channels, connected swamps	Large backwater swamps, rice fields
25	Elm Bayou	This last reach is a swamp. Several avulsions and distributaries empty into continuous backwater swamps. Man made irrigation channels run parallel to the main channel to route water to rice fields.	Backwater channels, connected swamps	Backwater swamps, channel avulsions, man made irrigation channels

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