HYDROLOGIC MODELING OF NAVASOTA RIVER SUBCHANNEL INUNDATION

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

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Anastomosing rivers are multichannel systems characterized by a definitive main channel and semi-permanent sub-channels that intertwine with the main channel in their planform. This semi-permanence of the sub-channels is largely associated with flows that have been recognized to be fed by overbank flows from the main channel. The Navasota river on the coastal plain of Texas is an anastomosing river with ephemeral anabranches dependent on main channel over bank flow. This study determines the river stage at which the main channel becomes laterally connected to anabranching channels by surface water. The chosen study site on the Navasota is located at Democrat Crossing road that is downstream of U.S. Geological Survey gaging station 08110800 at Democrat Crossing road.. The purpose of this work is to monitor the interactions of four downstream anabranches within a .5-km radius. Lateral connections between the main channel and sub-channels are determined using a two-dimensional hydrodynamic model that was developed using a LiDAR-based digital terrain model and calibrated/validated using acoustic and topographic surveys conducted in the field. Preliminary analysis suggests there are 3 stages of connection, (1) exclusively the main channel, (2) lower level anabranch connections, and (3) upper level anabranch. The riverine landscape of the Navasota River shelters high levels of ecological diversity and surface water connections within a river reach can impact the overall

health and evolution of these riverine ecosystem. This project provides a case study to promote knowledge of the flow dynamics of anastomosing geomorphology and water resource management applications within and upstream of the study site to help mitigate flooding hazards and help manage the riverine ecosystem.

DEDICATION

Dedicated to my parents for always supporting my education and providing me with encouragement.

ACKNOWLEDGEMENTS

I would like to thank Dr. Inci Guneralp and Cesar Castillo for their pursuit in having undergraduate students engage in scientific research outside of the classroom. The members of the Fluvial Dynamics lab; Yair Torres, Andrew Vanderheiden, Billy Hales and Joseph Wade in particular for helping me conduct field data collections. Thank you to FEMA for providing preliminary Digital Elevation Model data. I am thankful for funding from the Texas A&M College of Geosciences, Department of Geography, Department of Environmental Studies and High Impact Learning Experience (HILE) and equipment from Texas A&M GEOSAT. Finally, my parents for supporting me in my endeavors financially.

NOMENCLATURE

HECRAS	Hydrologic Engineering Center's River Analysis System
TPWD	Texas Parks and Wildlife Department
Lidar	Light Detecting and Ranging
TNRIS	Texas natural Resource Information System
NRCS	Natural Resource Conservation Service
TxDOT	Texas Department of Transportation
GPS	Global Positioning System
V	velocity vector
R	hydraulic radius
∇H	surface elevation gradient
n	Manning's roughness coefficient

CHAPTER I

INTRODUCTION

River Classification

There are currently four river planforms recognized in the literature; (1) straight channels, (2) meandering channels, (3) braided channels and (4) anabranching channels. While the first three mentioned are easily identifiable and widely studied, the latter planform contains ambiguous genesis and multiple classifications within the definition of anabranching rivers. One classification challenge mentioned in many papers is that anabranching rivers often contain some combination of straights, meanders and braided channels at a geographically large scale; such is the case with the nine largest rivers in the world; Amazon, Congo, Orinoco, Yangtze, Madeira, Negri, Brahmaputra, Japura, and Parana (Latrubesse, 2008). This occurrence has been noted and taken into consideration if anabranching channels should be considered an overarching classification for river planforms. Another aspect of anabranching rivers is the various definitions that exist in the literature. Makaske (2001) defined anastomosing rivers, a type of anabranching river, as requiring the composition of multiple interconnected channels enclosing a floodplain excluding bifurcation by convex upward bar formations, while others have simply defined the planform as requiring multiple distinct channels. Field and Lichvar (2007) make distinction between anastomosing and braided channels by distinguishing between evenly distributed flows of braided channels and main channel overbank flow feeding smaller anabranches. Papers have been published (Nanson & Knighton, 1996) to help understand the formation, duration and geographic influences of anabranching rivers which has led to multiple classifications of anabranching rivers.

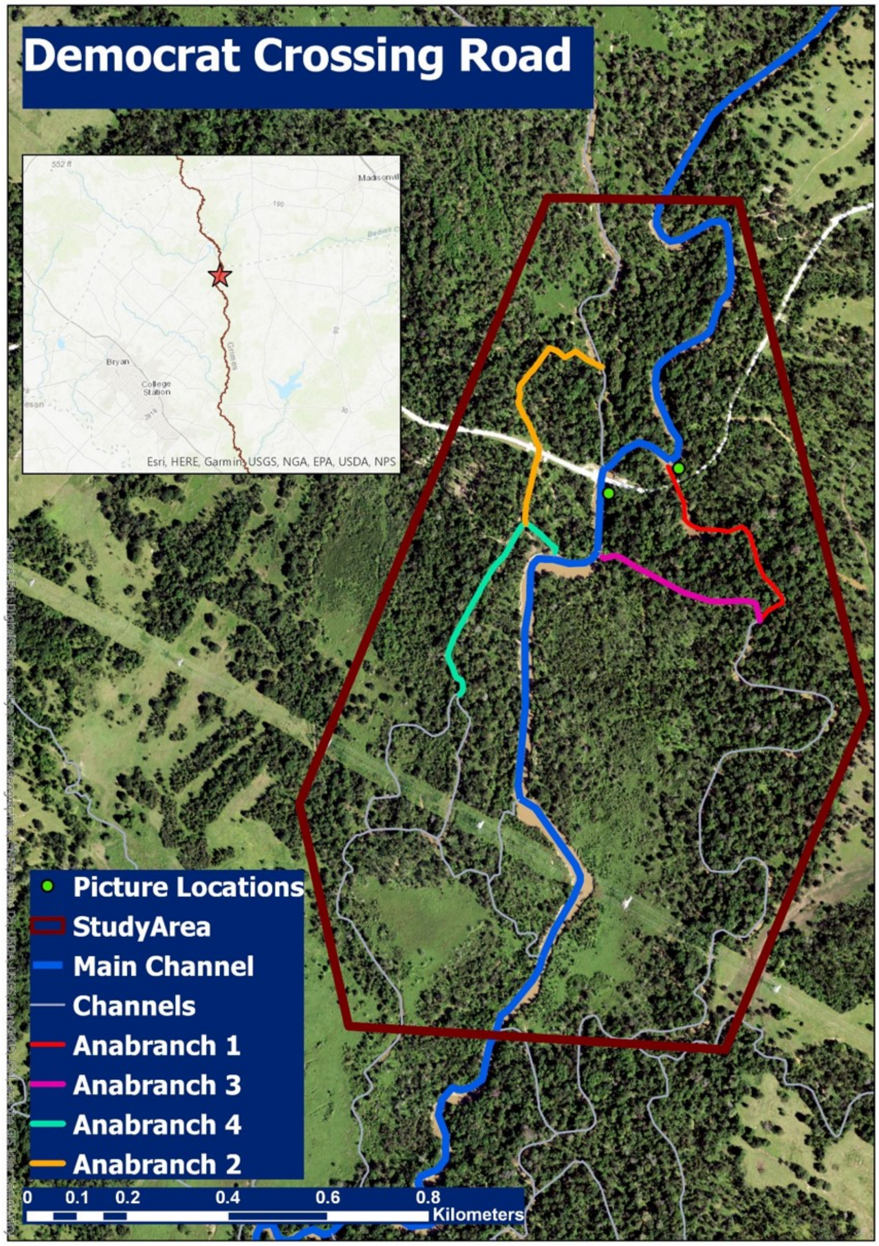

Figure 1. Map of the Democrat Crossing road study area and the studied anabranches.

The Navasota River is on the coastal plain of Texas and it is part of the Brazos River Basin that characterized as having a meandering planform. As documented by Jonathan Phillips (2009), the Navasota contains more than ten avulsions and multiple semi-active sub-channels dependent on the stage height of the river (Figure 1). The current body of knowledge doesn't include any other anabranching river in the coastal plain of Texas and is a small anabranching river in comparison with the more studied examples such as portions of the Parana river and Columbian river (Nanson & Knighton, 1996). Due to the research site being fine sediment and low stream power, the only anabranching river type detailed will be anastomosing and sand dominated island-form rivers. During field-visits in May of 2018, in situ observations showed anabranches disconnected from the main channel streamflow due to low stage heights (Figures 2, 3, 4, 5). The information presented leads to my overarching question: *When the semi-active sub-channels are connected and not connected?*

Objectives

Determining when the sub-channels allows the development of water resources management practices in relation to providing dam release rates to keep the sub-channels inundated and furthering the literature for the classification of anabranching rivers by providing a case study with a river in Texas; a region that typically has the exclusive meandering planform. The objectives of this project are to (1) determine the flow conditions at which the semi-active sub-channels are connected to the main channel and (2) evaluate the channel activity over time from the gage data. Data collection and constructing a model are also necessary in conducting this research. By collecting the required data to build a numerical model, the stage heights required to cut off the anabranches can be identified through simulations.

Figures 5 – 5. bifurcation located at the bend of the main river exposing alluvial deposits dividing the main channel from the anabranch during low flow in the summer (Figure 1: top left & Figure 2 bottom left) juxtaposed with over flow of the main channel during medium flow (Figure 3: bottom right) and high flow (Figure 3: bottom left).

CHAPTER II

LITERATURE REVIEW

Anabranching Rivers

Planform formation of anabranches for the “umbrella term” classification of anabranching rivers has been linked to two processes of channel flow diversions, known as avulsions and depositional alluvial islands, bifurcating the channel until the older channel is no longer active. Avulsions occur from scouring of the channel’s bank eventually creating a new path for the river to take, while alluvial islands aggregate out of the channel over time from alluvial deposition (Makaske, 2001; Nanson, 2013). Strictly studying avulsions has shown initiating factors to be the blockage of large debris, the accumulation of alluvial bed material, or exceptional floods.

The main sources in the genesis of anabranching rivers rely on an alluvial channel’s combination of stream power, sediment characteristics and in some cases vegetation (Makaske, 2001). These factors have led to Nanson and Knighton’s six classifications of anabranching rivers based on stream power, sediment size and morphological characteristics (Nanson & Knighton, 1996). These six types are anastomosing, sand dominated island-form rivers, mixed load laterally active rivers, sand dominated ridge-form rivers, gravel-dominated laterally active rivers and gravel-dominated stable rivers; which progressively increase stream power along with sediment size indicated by nomenclature.

Anastomosing rivers characteristically have fine grain cohesive sediment, low energy streams with little lateral activity characterized by wide alluvial islands with respect to channel width and located in low elevation gradient areas. In the case of low stream power small rivers with cohesive clays such as the Navasota, the erodible banks are stabilized with well-developed riparian vegetation and contain alluvial islands (Nanson & Knighton, 1996). The riparian vegetation has shown to help maintain a channel width/depth ratio that is favorable to bedload transport (Figure 6). Within anastomosing rivers there are three subgroups; (1) hyper-humid organic, (2) humid organo-clastic and (3) semi-arid mud dominated systems. Sand dominated island-form rivers develop narrow channels around wide islands due to vegetation, slow accretion in the alluvial portion of the river in comparison to anastomosing rivers and scouring of new channels from the floodplain near tributary portions (Figure 7).

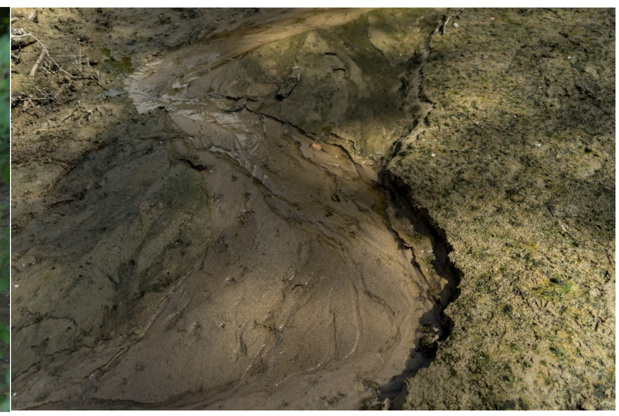

Figure 6 (left). An anabranch during low flow with a high amount of vegetation preventing bank erosion. Figure 7 (right). Sediment composition of the channel consists of silty-loam clayey-loam.

Numerical Modeling

While there are several approaches for mapping inundation such as remotely sensed imagery from past events, numerical models are designed to computationally model past and potential flooding events (Horritt and Bates, 2002; Williams et al., 2013; Komi et al., 2017; Sanyal & Lu). There is a plethora of two-dimensional numerical modeling software to choose from, the more widely used program is the Hydrologic Engineering Center's River Analysis System (HEC-RAS) (Quirogaa et al., 2016; Romali, 2018). This open-source program was created by the United States Army Corps of Engineers and is the government standard for modeling riverine flood inundation and is used to produce FEMA flood maps.

Numerical modeling consists of numerical solutions to the Navier-Stokes three dimensional differential equations, two-dimensional shallow water equations such as the diffusive wave equation and one-dimensional shallow water equations (Bates & Roo, 2000; Williams et al., 2013; Komi et al., 2017). The dimensional aspect of these models relates to flood propagation in relation to the river in finite volumes. The largest problem with numerical modelling in its current state is the computing power required for it. Software simulations are often simplified and require geospatial restrictions such as simulation area size limitations and larger area computation cells which generalize data over larger areas to simplify total processing required. A one-dimensional model lacks the capability to accurately simulate channel overflow as accurately as two-dimensional models. (Gharbi et al. 2016). Moreover, two dimensional models work well low relief areas. Three dimensional models are often times too computationally taxing for widespread use for large applications (Merz, 2012). Inundation types such as coastal or fluvial also take into account in respect to numerical modelling. Coastal modeling requires different software such as the coast modelling system while riverine models require software such as HEC-RAS. The overwhelming majority of the application use has been to analyze and predict single channel straight and meandering rivers in close proximity to urban areas and cities (Bellos, 2012). One of the more difficult and less published numerical modeling simulations is modeling multi-channeled braided rivers and anabranching rivers and/or full riverine networks (Williams et al., 2013; Jafarzadegan et al., 2018).

HEC-RAS was specifically designed to simulate one dimensional steady flow, one- and two-dimensional unsteady flow, sediment transport computations, and water temperature/water quality modeling (Brunner & CEIWR-HEC, 2016). By implementing the terrain conditions such as elevation and roughness values, the water input and output locations, along with a time-step interval of flow; HEC-RAS calculates the hydrodynamics of the area. As with all simulations of nature, computation is designed to model nature on varying levels of complexity. Because of this complexity of nature and the limitations of computational power, current modelling software uses simplified equations. HEC-RAS has multiple numerical modeling methods dependent on the study area and what the desired output is. This project uses a two-dimensional diffusion-wave model to simulate the pressure forces in addition to gravity, friction, and potential backwater effects. The exact equation used for velocity calculations driven by gravity and bottom friction forces is known as the Diffusion-Wave Form of Momentum Equation (Equation 1).

Equation 1.

$$V = \frac{-(R(H))^{2/3}}{n} \frac{\nabla H}{\nabla H^{1/2}}$$

Where V is the velocity vector, R is the hydraulic radius, ∇H is the surface elevation gradient and n is the empirically derived Manning's n. This allows gravity-controlled flow in a shallow water body to disregard the Coriolis, turbulence, advection and unsteady terms of the momentum equation.

CHAPTER III

METHODS

Creation of a Digital Elevation Model Using Lidar

As stated by Williams et al. (2013), the key input for building a flood model is having elevation data for the area of interest, i.e. the Clear Lake quadrangle of Texas. Terrain data allows numerical models to calculate the slope and direction at which water flows through the channel and/or inundates the surrounding area. The first task to accomplish is to acquire Light detection and ranging (LiDAR) and convert it to a Digital Terrain Model (DTM). LiDAR uses high frequency lasers, a GPS, and an altimeter to produce and orient high resolution (Liu, 2008). This project utilizes intercounty-level preliminary digital terrain model from FEMA that is scheduled to be released to the public in the future and lidar collected in 2010 from the Texas Natural Resource Information System (TNRIS). ArcGIS Pro was used to convert the LiDAR data into a ground level DTM by exporting only the ground classification calculated in the LiDAR for the final DTM at one-meter resolution (Figure 8). Both DTMs were combined into one-meter resolution, which at one-meter resolution the data provided for the Navasota has the detail necessary to produce a suitable DTM of the non-inundated areas for the model.

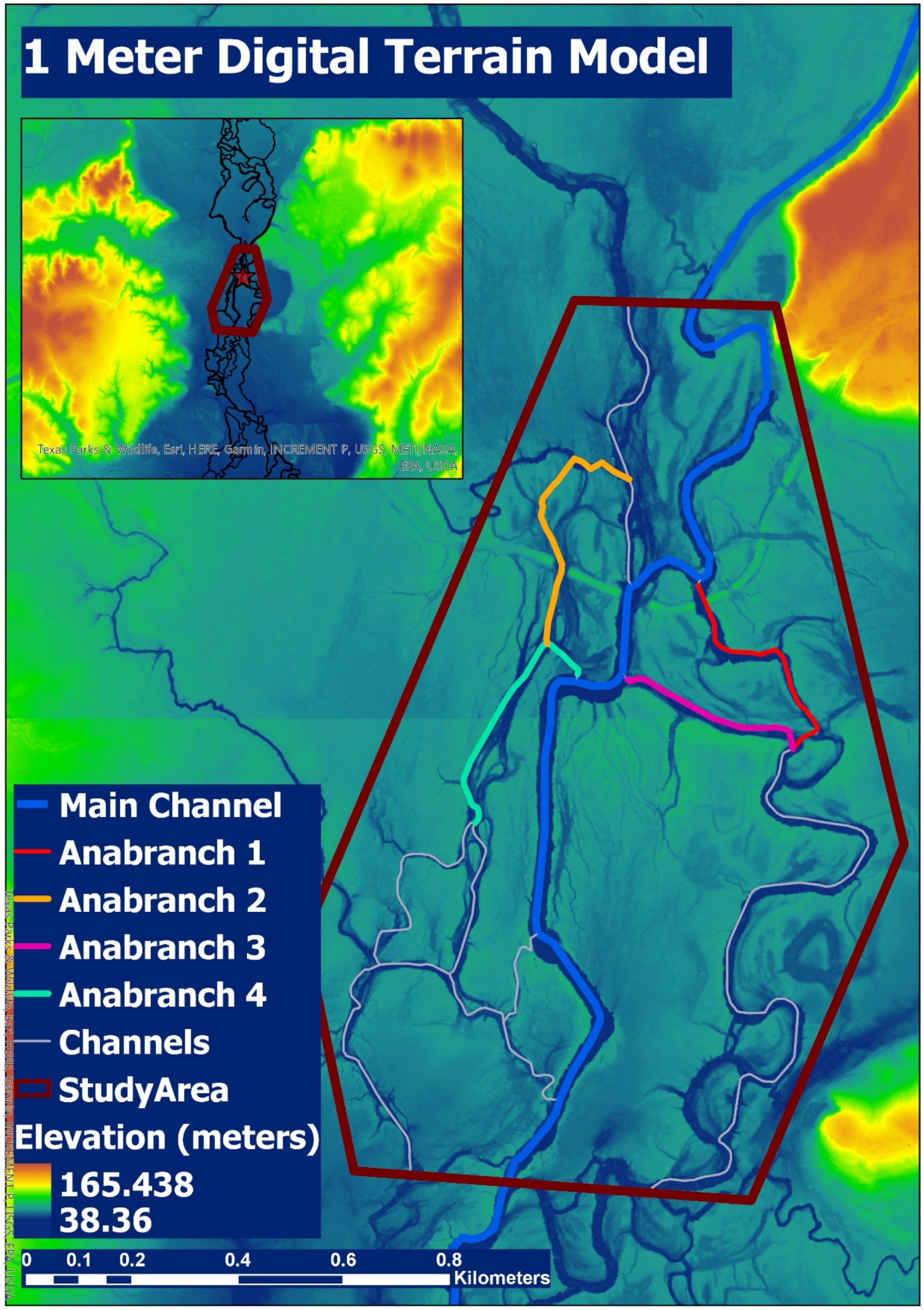

Figure 8. Digital terrain model of the study site showing the land relief in meters, and a more detailed drainage network.

Field measurements were acquired to supplement the lack of channel bathymetry and used for validation of the model. Channel geometries are a necessary component for accurately depicting and analyzing riverine geomorphology and hydraulics (SonTek/YSI, 2008). An Acoustic Doppler Current Profiler (ADCP) was deployed at different segments of the main river channel and anabranch bifurcation locations during different discharges to capture data at varying sections and flows. The transects were then used to interpolate the channel sections with no bathymetric data and incorporated into the LiDAR by interpolation of the Z-values of the channels. Through this method, the bathymetry has a rough estimation instead of a channel geometry dependent on the amount of water in the channel the day the LiDAR was collected. The discharge information provides true observations on how much water is traveling through the riverine system, which will be used when establishing simulation flows for calibration (Brunner & CEIWR-HEC, 2016; Teng et al., 2017). The reason why bathymetric interpolation is required rises from the lack of publicly available green light bathymetric LiDAR taken during airborne LiDAR missions. Due to the feasible accessibility, the location of these transects were scouted using aerial imagery, but ultimately determined by in situ accessibility to the river (Figures 9 - 12).

At the study site geospatial waymarks were collected of various channel banks, that were not completely submerged, with the use of a Real Time Kinematic Global Positioning System (GPS) points. By collecting this data, the areas that the ADCP cannot record are still captured. On 19 October 2018, a GPS was used to collect the water’s edge during a flooding event to be used as validation data, during which locations were deemed inaccessible during the recorded flooding event due to safety concerns and as such the measurements used were taken next to bridges.



Figure 9. ADCP calibration by the river. Figure 10: Base station and control station in view of the canoe pulling the ADCP. Figure 11: Docking the canoe in preparation of transect data collection with a person on both banks of the river. Figure 12: Pulling the ADCP perpendicular of the channel banks to collect bathymetric and flow structure data.

Stream flow data was acquired from the National Water Information System (NWIS) USGS gage 08110800 upstream of the study site. Records of the discharge and stage height of the study site starting from 1 October 1996 through 25 March 2019 allow for observed flow data implementation for the numerical model and data analysis past channel activation.

Two-Dimensional Unsteady Flow Simulation

In HEC-RAS, I imported the DTM and outlined the study area to apply geometric calculations for the topography of the study area. For inflow and outflow, boundary conditions were determined to be at the main channel inlet and the main channel cross section at the southern end study site. The leeway for computational stress allowed for the two-dimensional flow area mesh to be a five-pixel by five-pixel computational cells or about, thus allowing computations to occur every 7.62 square meters.

To determine the surface roughness for the terrain/ hydraulic interaction, Manning's roughness coefficient was calculated by importing the Texas Parks and Wildlife Department's (TPWD) Ecological Mapping Systems of Texas classification and approximating individual classification values based on the Natural Resource Conservation Service (NRCS) of Kansas' average values (Figure 13). Manning's roughness values are used to characterize the land's surface roughness allowing the model to simulate surface drag interaction between the ground and water. Historically this coefficient, while numerical in design, has been determined by subjective classification based off what is deemed appropriate in the field. In modern times, journals have published objectives to quantify determination using computations analysis.

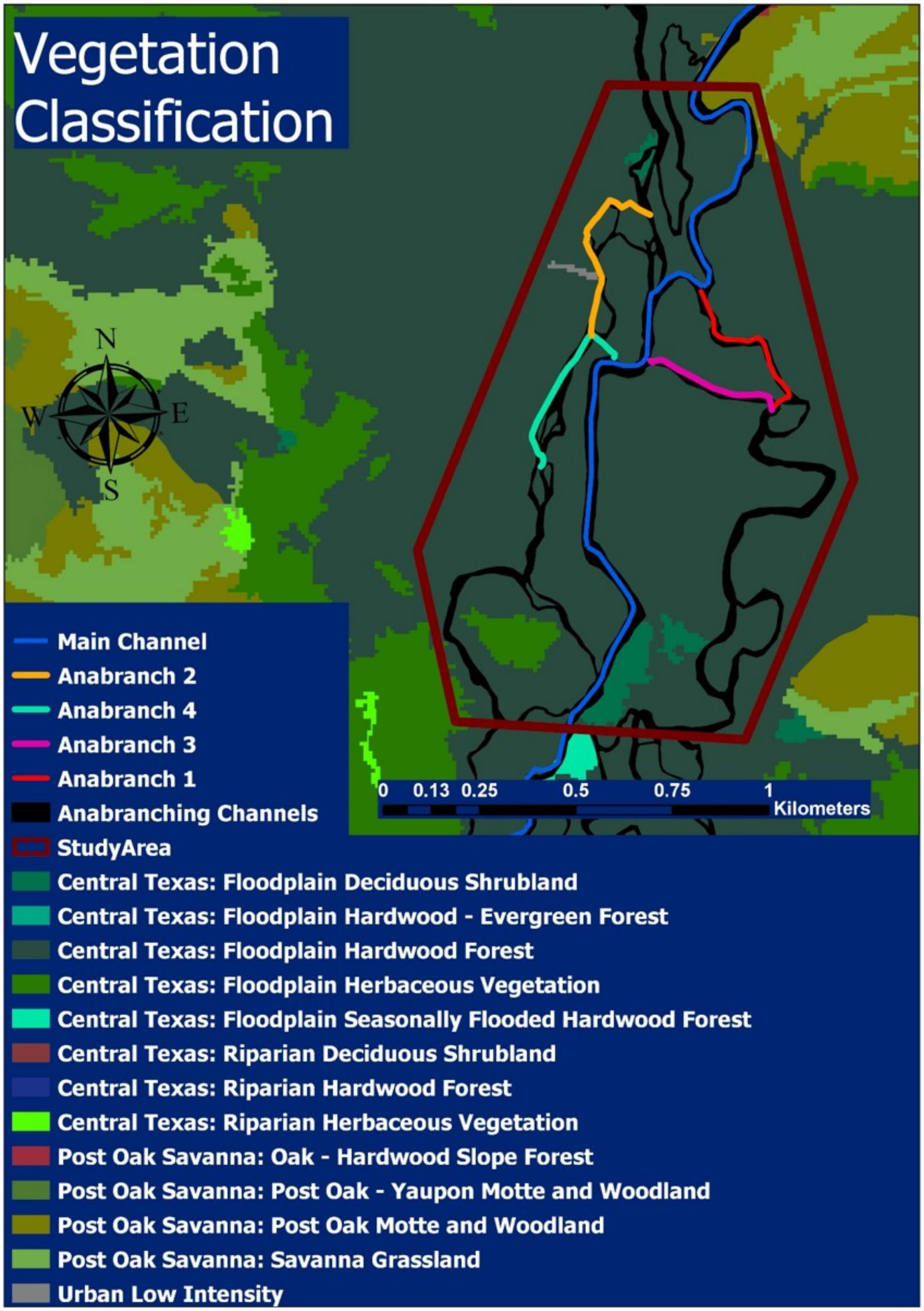

Figure 13. Vegetation classification map indicating that majority of the study site consists of flood plain hardwood forest.

Once calibrated, the unsteady flow data will run constant discharge for a month-long period allowing the model time to add a pseudo initial flow to the simulation and improve final inundation results. The results will then be visually evaluated to assess which channels are active and not active during varying flows. With the sub-channel activation flows determined the stage heights can be applied to a graph to determine how often the channels are or are not inundated by evaluating the daily stage data in relation to the calculated activation heights.

Calibration and Accuracy Assessment

To check the accuracy of the model, the gage station and ADCP measurements taken earlier will be used as comparison. Traditionally, models would simulate recorded event flows and compare the flood extent with aerial imagery of the flood event for model validation (Sanyal & Lu, 2004). Due to canopy coverage caused by the riparian vegetation surrounding the floodplain, it is impossible to measure the flood extent using aerial imagery. Alternatively, because the ADCP produces GPS and velocity measurements, it is possible to use the velocity as a constant input discharge for the model. The product of the simulation will produce results that can be compared to the field measurements using a chi squared "goodness of fit" statistic.

CHAPTER III

RESULTS

Results from the chi squared test indicate a ten percent accuracy probability for the model. The observation versus simulation inundation depth comparison showed that simulation was inundated and within a third of a meter depth at three points in comparison to the observed recordings. The other seven points were outside of a third of a meter or were not inundated at all. Anabranches one, three and four showed activation and through-flow at 1.5 meters. Anabranch two showed inactivity at 1.5 meters (Figure 14). Using the stream gage daily stage data, the comparison of stage height and sub-channel activation revealed that anabranch two was historically active sixty-seven percent of the time between October first, 1996 and March twenty-third, 2019 (Figure 15). The average monthly stage height indicates July, August, September, and October as the month most likely to have flows below 1.5 meters.

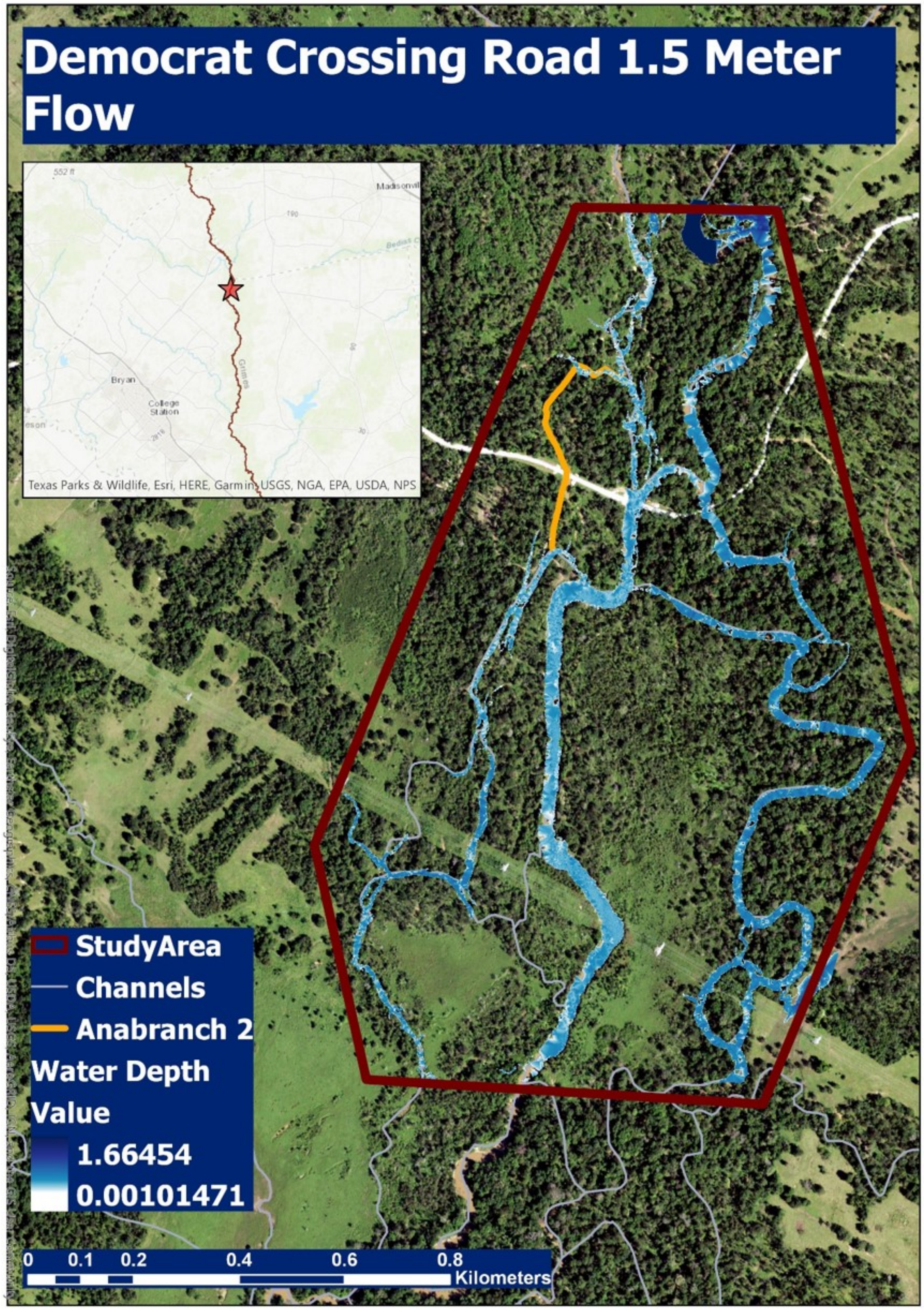

Figure 14. HECRAS water extent output showing channel inundation at the simulated 1.5 meters gage height with anabranch 2 displayed as inactive.

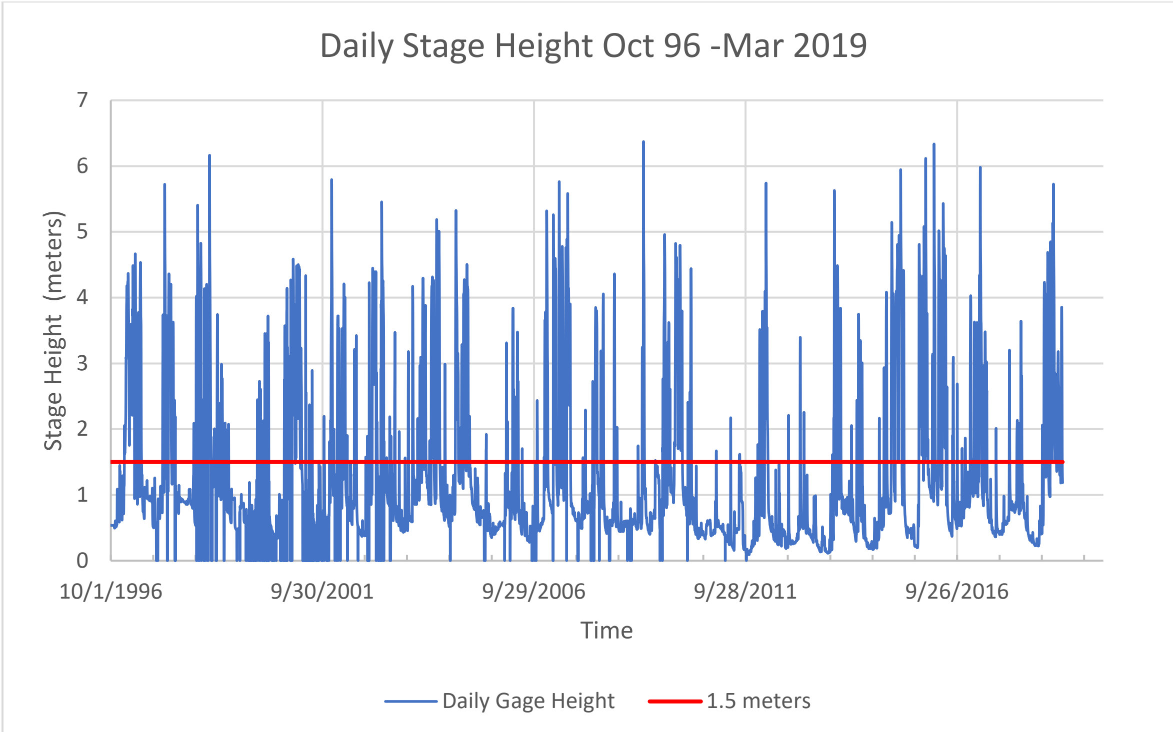

Figure 15. Daily stage data from USGS gage 08110800 upstream displaying data from October first, 1996 to March twenty-third ,2019. The red line indicates the separation between recorded heights above and below 1.5 meters.

CHAPTER IV

DISCUSSION AND CONCLUSION

Problems

The critical issue with this project has been data collection. The amount of personnel and equipment required to collect the data while the river is at a favorable condition requires an immense amount of preparation and coordination to collect data was unfeasible at the time this project was conducted. In total there were five trips taken to the field site to collect data and using the ADCP is a long and physically taxing process due to setup and manual labor. More bathymetric data is required to fill in the spatial gaps of the channel. At the current stage of the project, there is bathymetric data for a portion of the main channel and transects located at the bifurcation of the anabranches. Once more data has been collected, roughness value calibration will be conducted to fine tune the model and increase the accuracy probability. With more measurements the intervals or gaps between the transects would be smaller, thus allowing less simulated geometries and more accurate representation. This is crucial because the gradient between the main channel and the avulsion/bifurcation elevations determines at what level the sub-channels are activated.

Literary Impacts

As mentioned in the literature review, the Navasota has multiple channels that intertwine with the main channel, a low discharge rate, erodible clastic banks rooted from vegetation, and is in a low gradient of relief area. These characteristics indicate that the Navasota meets the requirements of being a humid organo-clastic anastomosing river. Given its formation in an area surrounded by meandering channels, further studies of this river can help identify and weigh the geomorphic processes responsible for the formation of anastomosing channels. Indicated by Field and Lichvar (2007) the main channel overbank flow does feed the anabranches, but most of the literature only studies arid land anabranching rivers or larger systems that do not receive discharge measurements low enough to study anabranch activation. This lack of peer reviewed knowledge leaves an enigmatic definition of an anabranch. Jonathan Phillips referred to the anabranches as semi-active sub-channels which raises the idea that these channels might not meet the criteria to be classified as anabranches due to intermittent channels. Lastly, while not evaluated in this project there are semi-active sub-channels that have been observed actively flowing only during high events relative to past flows Because of the potential for anabranches only active less than half of the year, the question that should be further pursued is at what point do these semi-active sub-channels become classified as old abandoned channels?

Environmental/Water Management Impacts

There are seven lakes with man-made dams impounding water upstream. While no analysis was done to determine the correlation between the dams and discharge measurements, limited channel flow due to water management practices upstream is a probable factor affecting the ecosystem downstream. Conducted before the building of dams, Clark (1973) hypothesized that the population of current dwelling fish would decrease, and the lentic dwelling species would increase. With low stage heights the anabranching channels are uninhabitable and cease to provide migration corridors and habitat for fish. For flora like the endangered central Texas endemic Navasota Lady Tresses,' a higher soil moisture is necessary to survive and propagate. By the continuation and expansion of this project, information can be presented to water management agencies to potentially develop dam release regulations meant to improve and sustain the ecosystem downstream.

Conclusion

The Navasota meets the general criteria to be classified as an anabranching river. The river along with its surrounding floodplain houses a large diversity of fauna along with an endangered endemic plant species. The anabranches of the Navasota showed seasonal intermittency, with anabranch two showing to be inactive thirty-three percent of the last twenty-one years. Further data collection is needed to improve the model and achieve more accurate representation of the river at low stages. This case study brings forward the ambiguous classification of the sub-channel or past-channel given main channel stage height dependency along with water management implications in relation to the upstream dams impounding water for recreational lakes. Stage height dependent sub-channels located down stream of dams raises the question of if there should be required dam releases in order to keep the channels active downstream to provide habitat for flora and fauna of the region.

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