A HISTORICAL INVESTIGATION OF MORPHOLOGICAL CHANGE IN THE RIO GRANDE CHANNEL BELOW BROWNSVILLE IN RESPONSE TO UPSTREAM HYDROLOGIC CONTROL INITIATIVES

THESIS

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CHAPTER 1

INTRODUCTION

This thesis addresses the question: How have upstream hydrologic control initiatives changed the morphology of the Rio Grande channel below Brownsville? Historical data, discharge data, maps and aerial photographs were analyzed qualitatively and quantitatively to answer the question. The problem, or question, addressed in this work is important because it furthers understanding of the geomorphology of the Lower Rio Grande Valley (LRGV) and the downstream effects of hydrologic control initiatives, such as dams. Perhaps more importantly though, this problem is worthy of investigation because the Rio Grande serves as the international boundary between the United States and Mexico. Morphologic changes in the Rio Grande's channel are, in effect, changes to the international boundary. Channel change and the evolution of the river are part of the natural history of the LRGV, but human settlement in the region and the adoption of a wandering river as the division between two countries, necessitated control of the river. Ironically, human intervention has triggered morphologic channel changes that have made the boundary less defined, and therefore, more uncertain.

The Rio Grande's drainage basin extends from the mountains of Colorado to the Gulf of Mexico, but the flow of the river is not continuous. It is interrupted by several large, and many small, dams and other hydrologic control structures (Figure 1).

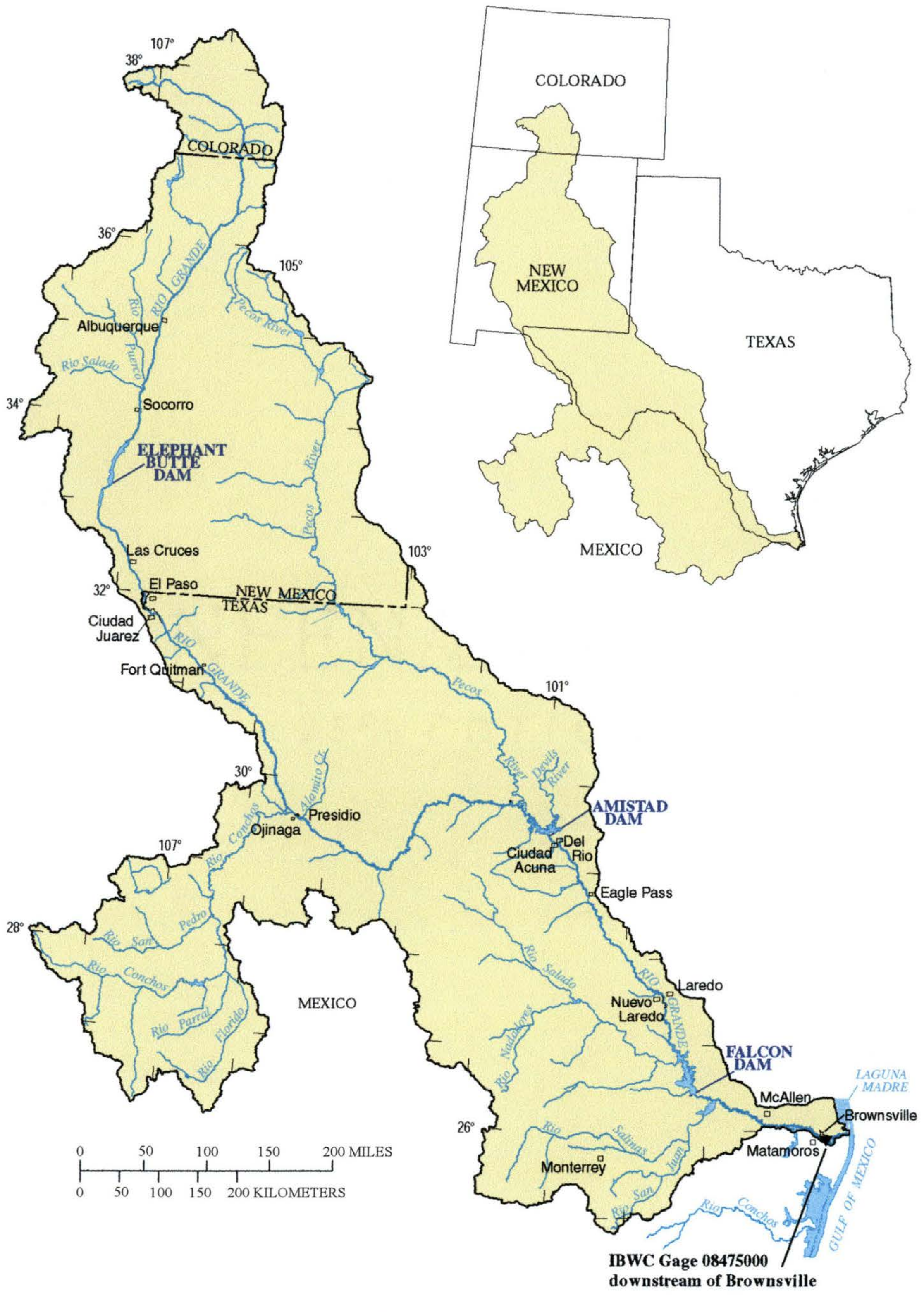

Fig. 1. Rio Grande Drainage Basin and Major Dams
Modified from USGS Fact Sheet No. 074-00, July 2000

A reach of the Rio Grande, beginning downstream of Brownsville, Texas was chosen for this study because it is downstream of all major hydrologic control initiatives (Figure 2). Though the scope of this work is focused on a section of the river that is only about 50 kilometers (30 miles) long, activities occurring throughout the Rio Grande basin have impacted the study area.

Before evaluating how hydrologic control initiatives have influenced the morphology of the Rio Grande in the study reach, it is valuable to first establish a context in which to measure change. Chapter 2 accomplishes this by discussing the variables that control river morphology and how rivers are classified given a set of controlling variables. The concept of dynamic equilibrium is introduced to describe how a river system responds to changing variables. In this chapter, potential answers to the research question begin to arise from the conclusions of the literature discussed. Channel width is expected to narrow and the length of the river's thalweg is expected to increase due to sedimentation that results from curtailed discharge.

The study reach flows through the LRGV, one of the fastest growing areas in Texas with a rich history of agriculture made possible by the Rio Grande. The history of water control initiatives on the Rio Grande in the study reach follows the history of development of the LRGV and of the Rio Grande basin as a whole. This is the subject matter of Chapter 3, which provides further context for morphologic change. In this chapter, the anthropogenic variables that influence channel morphology are discussed.

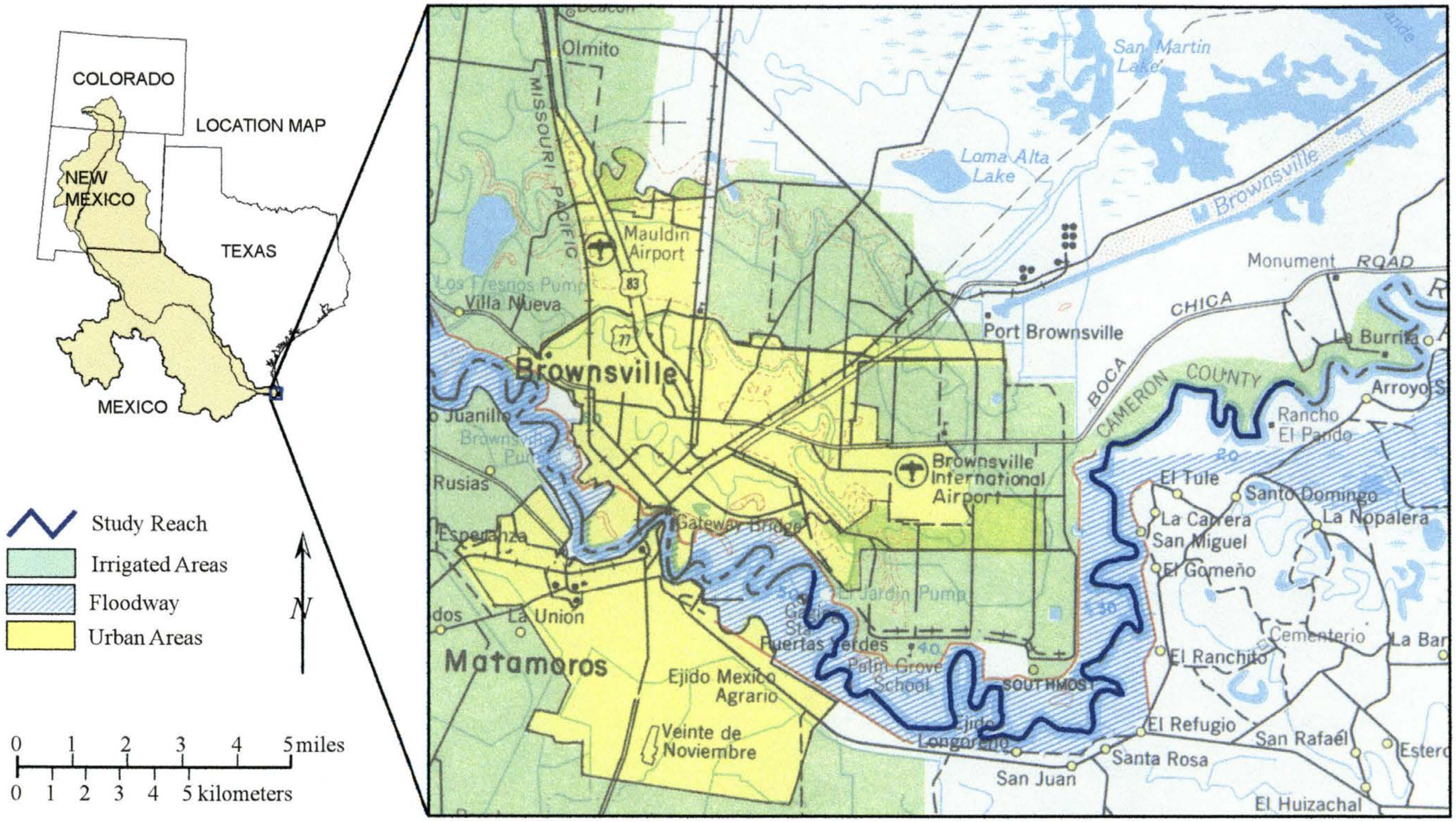

Fig. 2. Site Map Showing Extent of Reach
Modified from IBWC map: Lower Rio Grande Valley, United States and Mexico, Flood Control Works and Irrigation Developments, date unknown

The methods used to evaluate and quantify morphologic change are presented in Chapter 4. To accomplish the goal of quantifying morphologic change, instead of just qualitatively describing it, a geographical information system (GIS) was used. The main focus of this chapter is on the GIS process that was employed. This process should be regarded as more than a series of instructions. The ability to superimpose historical data using GIS facilitates a greater understanding of how the Rio Grande has changed over time.

Finally, the results of the study are presented and avenues for additional research are discussed. A century of hydrologic control initiatives has dramatically and, perhaps irrevocably, altered the morphology of the Rio Grande. The river has experienced such extreme disturbances that it barely resembles its natural state. The quantitative results of this study show conclusively that hydrologic-control initiatives have dramatically influenced the morphology of the Rio Grande downstream of Brownsville and have taken the river out of equilibrium.

CHAPTER 2

VARIABLES CONTROLLING RIVER MORPHOLOGY

This chapter describes the variables that control river morphology so that the Rio Grande can be examined in a theoretical context. Though an ideal context or model that neatly predicts river morphology given a set of conditions or variables doesn't exist, it is valuable to begin to create a theoretical context in which morphologic change can be evaluated (Richards 1987). The factors that allow for a shift in river morphology will be explored and empirical river data will be examined to illustrate how rivers respond to disturbances.

Discussion of Variables

The morphology of a river and its floodplain are determined by a multitude of factors, or variables, that include the velocity of flow, sediment load, the geology of the river channel, gradient and climate (Leopold and Wolman 1957; Pickup 1976; Shumm 1977; Richards 1982). Regime theory states that channel geometry is a function of the variables that control width, depth, slope and meander form (Knighton 1988). In addition, anthropogenic forces such as land use in the floodplain and the impoundment of rivers by dams, have significantly altered the natural hydrology of rivers (Petts 1979;

Church 1992; Collier, et al. 1996; Milhous 1997). The forces that act to change rivers may be gradual, occurring over long periods of time, or they may be dramatic and occur during such catastrophic events as floods or dam impoundment.

It is clear that the impact of some variables is dependent on time. For this reason, time (or duration) is perhaps the most important variable to consider when studying fluvial geomorphology. Time not only exerts an important control over the work that a river is capable of doing (e.g. how much sediment it carries, how it alters the landscape), but it also plays a role in how a river responds to changes in other variables. River responses to changing variables are complex and may involve a series of responses with lag times (Park 1995).

River responses to disturbances may occur immediately or they may take many years, making it difficult to directly associate disturbance with response. Knighton (1987) discusses the downstream effects of reduced discharge in the Platte River caused by an upstream dam. A ten to thirty percent decrease in discharge reduced channel widths proportionately, but the change took place over fifteen years. Tracking river responses to change is not only complicated by lags in time, but also by spatial lags. The spatial discontinuity of channel change and adjustment has been well documented. There is generally not only a local response to a disturbance, but also a series of downstream and upstream responses to the disturbance (Knighton 1987).

It is important to note that many environmental variables are multivariate and interdependent (Richards 1987). What follows is an illustration of the multivariate nature and interdependence of river variables. Reservoir construction causes decreased discharge, which in turn, causes sedimentation and vegetation encroachment of the river channel downstream of the dam. Vegetation in the channel then causes further sedimentation and sedimentation reduces gradient. A less pronounced gradient encourages more sedimentation because a decrease in slope, decreases a river's ability to transport sediment since there is an inverse relationship between discharge and slope (Schumm and Khan 1972; Richards 1982; Knighton 1998). Furthermore, reservoir construction might lead to land use changes in the floodplain that also affect the river simultaneously.

Empirical data have been used to construct models of river behavior using historical data pertaining to known variables. Both river piracy and an extreme drought starve a river of its discharge in the same way that a dam does. These two naturally occurring phenomena produce the same changes in morphology, so knowledge of river behavior in response to climate change or historical floods helps to understand and predict the changes in morphology that occur because of dams.

Geomorphologists have also constructed a viable model that explains the morphology of meandering rivers using empirical field and gaging-station data. It is well understood that rivers cut their banks on one side where water is moving the fastest, and build point bars, or sandbars on the opposite side where the current is more sluggish. This process allows rivers to meander and move laterally, while maintaining a consistent channel width (Schumm 1977; Richards 1982; Dietrich 1987; Leopold 1994).

A careful, time-series evaluation of sandbars can be indicative of the stability of a meandering river (Church 1992). Unvegetated or moderately heavily vegetated sandbars suggest that a meandering river is stable because it is competent enough to move its sediment load. On the other hand, an overgrowth of vegetation on sandbars is testament to the fact that sandbars are immobile because the river has lost some of its competence.

Though there is no universal formula that describes the effect of the interaction of variables over time for all rivers, the behavior of particular rivers, in response to a change in a single or few variables, has been well-studied (Leopold and Wolman 1957; Pickup 1976; Baker 1977; Schumm 1977). All other things being equal (all other variables controlled), a decrease in discharge will produce sedimentation because less energy is available to transport sediment (Everitt 1993; Leopold 1994).

It is valuable to scrutinize whether the result is logically or directly linked with the cause. It would be an oversimplification to state that river impoundment causes sedimentation (Richards 1987). Rather, river impoundment has the effect of reducing discharge, and therefore causes sedimentation. Another cause of sedimentation downstream of dams is the absence of flood flows that previously flushed out sediment from river channels (Kondolf 1995).

Riparian vegetation can have a significant influence on river morphology. Riparian vegetation both stabilizes and over-stabilizes banks against erosion (Ferguson 1987). Naturally occurring floods produce overbank flows that interact with native, riparian vegetation and allow for the building and the rebuilding of riverbanks and floodplains. The reduction of overbank flows therefore, causes the floodplain to be disconnected from the river (Brown 1995).

In addition, non-native vegetation such as tamarisk (*Tamarix gallica and Tamarix aphylla*), also known as saltcedar, is more flood resistant than native vegetation and has the effect of over-stabilizing river banks. This over-stabilization encumbers the natural destruction and reconstruction of riverbanks and floodplains. If a river's banks are made overly resistant by vegetation and there is a lack of overbank flows, sediment is deposited within the river channel and the result is channel narrowing (Leopold 1994; Knighton 1998). Vegetation encroachment in the river channel itself leads to sediment trapping and facilitates aggradation and further narrowing. The term aggradation is referred to in this work as the proportionate in-filling of the river channel's bottom and banks.

River Classification

Geomorphologists have long tried to categorize rivers using discharge, width-depth relationships, bedload, bed and bank material and other criteria. Ideally, different river morphologies could be predicted and put into categories that were mutually exclusive. While many rivers fit neatly into categories, given a set of defining variables, others do not (Ferguson 1987). There are guidelines for river classification, but there is disagreement about categorizing rivers, in part because there are no definite lines or thresholds to distinctly confine the boundaries of categories.

The problem with fixing the lines or thresholds between categories is that there are transitory types of river morphologies straddling categories. For this reason, there has been a movement to think of river classification as a continuum of channel forms, rather than in terms of distinct categories (Leopold and Wolman 1957; Richards 1998). Still, there are some thresholds that can be used to 'type' rivers. In order to hold its place in a category, a river must be in equilibrium, or achieve a state of balance with controlling variables. When a river's morphology is out of equilibrium with controlling variables, a shift to a new morphology is taking place.

Dynamic Equilibrium

Leopold and Wolman (1957) were two of the pioneers of evaluating rivers and their floodplains in terms of their tendencies towards equilibrium. A river system is said to be in dynamic, rather than static, equilibrium because change or disturbance is relatively typical and frequent. Pure equilibrium is not feasible but dynamic equilibrium is achievable in a river system (Wharton 1995).

Rivers make morphological adjustments to floods, droughts and other disturbances constantly. Negative feedback mechanisms compensate for external disturbances and allow the river system to self-regulate. Rivers may tend more towards a steady state equilibrium where negative and positive changes oscillate and cancel themselves out around an average morphology, or the equilibrium responses might be more complex (Richards 1982). Deviations from mean flow conditions, such as during floods or droughts, may force the river out of equilibrium for a time, but the system responds to changes, adjusts, and reaches a new equilibrium when typical flow conditions return.

A river's ability to remain in dynamic equilibrium is dependent, however, on the river system's susceptibility to change (Knighton 1988). For this reason, it is necessary to distinguish between a disturbance that a river system can recover from or absorb, and a disturbance that is dramatic enough to take a river out of equilibrium. A dramatic disturbance might require a shift to a new equilibrium form and necessitate the adoption of a new morphology. Renwick (1992) defines *disequilibrium* as the dynamic state where there is a move in the direction of equilibrium, but the goal has not been reached, most likely because of a long response period, but after time, equilibrium will be reinstated. This term befits a river that is temporarily out of equilibrium because it is responding to a disturbance. A drastic disturbance can be thought of as one that exceeds a threshold (Knighton 1998). Renwick's definition of *non-equilibrium* describes a river system that cannot be identified by a characteristic set of conditions and therefore, a movement toward the previous equilibrium state is not evident and will not be achieved.

There is plentiful debate and little agreement surrounding the application of equilibrium concepts to river systems. For the purposes of this work, dynamic equilibrium is used to describe a river system that maintains its morphology after recovery from a disturbance. A river is out of equilibrium, or in a state of non-equilibrium, when it tends toward a new morphology (which might then achieve equilibrium) but that new morphology does not resemble the pre-disturbance form.

Ferguson (1987) discusses the difference between transient and persistent disturbances in a river system. For example, a seasonal flood might produce a transient change in a river, but when the flood has subsided, the river maintains its pre-flood morphology. Man-made disturbances tend to be more persistent. The construction of a dam for example, permanently and dramatically decreases the amount of discharge in a river system. The river is forced to change its morphology to adjust to the new long-lasting flow regime. Eventually, a river can achieve a new dynamic equilibrium with the reduced discharge, but the magnitude of the disturbance was so great that a new morphology must be achieved to reach equilibrium.

Geomorphically Effective Discharge

To say that a river is in dynamic equilibrium is to say that it is maintaining a consistent morphology and that the river system is able to respond to disturbances. The previous section discussed how decreased discharge caused by river impoundment can take a river system out of equilibrium because a threshold is exceeded. How is this threshold defined? To better understand why a river adopts a new morphology, it is necessary to know what constitutes a geomorphically effective event. This involves exploring the difference between disturbances that can be absorbed by the river system, versus those that disrupt equilibrium enough to spur a shift to a new morphology.

The type of discharge that controls channel morphology is referred to as dominant discharge (Leopold and Wolman 1957). Leopold (1994) used empirical data to come up with general principles relating to river channels and varying discharge. He found that a river's mean discharge tends to fill the river channel to about one-third of its capacity. Discharge that fills the channel, known as bankfull discharge, occurs about once every 1 to 2 years. These are the geomorphically effective flow events according to many geomorphologists (Leopold and Wolman 1957; Richards 1982; Leopold 1994). Wolman and Miller (1960) also found that short-lived, extreme flood events (those with a recurrence interval of greater than 10 years) were not as effective as higher frequency, more moderate flows.

Costa and O'Conner (1995) also evaluated the factors that make a flood geomorphically effective. They too found that even large volumes of water suddenly introduced into a river basin (in their study due to failure of a dam), do not necessarily cause dramatic geomorphic changes because of the short duration of such events. The impact of an extreme, rare fluvial event may be insignificant if a river has the capacity and time necessary to recuperate from it. The river can return to a dynamic equilibrium state if it is able to recuperate before the recurrence interval of the event (Richards 1982).

Still, there is much disagreement among geomorphologists concerning what type of discharge controls channel morphology (Knighton 1998). Some believe river morphology is a function of the latest major flood, whereas others believe it is the product of average discharge (Richards 1982). The reality is that there is no absolute rule. It is difficult to quantify the effect of dominant discharge, or geomorphically effective discharge on the morphology of a river when there are so many other variables exerting their influence.

In summary, this chapter presented the variables that can be used to help predict river morphology. Examples of river behavior were given in light of empirical data to facilitate an understanding of what factors control river morphology. The concept of dynamic equilibrium was used to establish thresholds between different types of river morphologies and to point out that there is a breaking point at which dynamic equilibrium fails and a shift in morphology occurs. Lastly, a discussion of what constitutes a geomorphically effective event was given. Chapter Five, Results and Conclusions, will evaluate the Rio Grande downstream of Brownsville, in terms of the changing variables that control river morphology, empirical data on river behavior and the concepts of dynamic equilibrium and geomorphically effective events.

CHAPTER 3

ANTHROPOGENIC CONTROLS ON THE MORPHOLOGY OF THE RIO GRANDE

Introduction

In an attempt to control the Rio Grande so that its behavior is more conducive to human settlement, human intervention has taken the river system out of equilibrium and the result has been dramatic change in river morphology. In the previous chapter, the variables that control river morphology in an undisturbed or equilibrium system were discussed. What follows here is a description of the anthropogenic activities that have changed controlling variables and therefore, altered the natural morphology of the river.

The Rio Grande is continually attempting to adjust to human hydrologic control measures, oftentimes generating a response that was not intended and is considered unfavorable to man. While it is difficult to predict river morphology in an undisturbed system where the variables are known and controlled, it is much more challenging to understand river behavior in the context of anthropogenic activities.

One of the reasons for this difficulty is the time lag between cause and effect. The effect of human activities may not be expressed immediately in the river system, or there may be a series of responses that occur when the river is adjusting to the change in phases. Because of these pulsed responses, it is difficult to equate a particular response to a particular cause. Another very important factor to consider when attempting to measure man's effect on the river system is the complication that arises when several variables, often interrelated, are acting on the river at once, or intermittently. This is the situation in the LRGV where the river has been dammed, diverted, lined with levees and revetments, and stripped of its natural vegetative buffer. All of these anthropogenic variables are acting on the river at once in some places, and in different combinations, and to varying degrees, in other places. To add to the confusion, counteracting variables are thrown into the equation at the same time. For instance, the restoration of parts of the river to an unmanaged, natural state works against the variables associated with intense management of the river.

This chapter first examines the study reach in the context of the entire Rio Grande drainage basin, because actions taking place throughout the basin influence the lower part of the basin where the study reach is located. After discussing some of the major hydrologic control initiatives taking place in the Rio Grande basin, this chapter will focus on the history of river control measures and diversions that have occurred in the LRGV. Hydrologic control measures on the Rio Grande occur on the river itself, but also on the river's tributaries and floodplain. It is important to make this point when examining the geomorphic affects of hydrologic controls on the Rio Grande because damming one of the Rio Grande's main tributaries may have as pronounced of an effect as damming the river itself.

The River as an International Boundary

The Rio Grande is approximately 3,060 kilometers (km) (1,900 miles) long, making it the fifth longest river in the United States (Day 1970). The river's watershed expands over three states and it serves as the international boundary between the United States and Mexico (Figure 1). The Rio Grande's management is thus complicated by the fact that it is subject to state, interstate and international water laws.

The Rio Grande has served as part of the international boundary between the United States and Mexico since 1848 (Day 1970). Because of the low gradient and low discharge conditions in some areas of the Rio Grande's path, especially near El Paso and the LRGV, the river's natural inclination is to meander. When the river meanders, it erodes its bank on one side where water is moving swiftly, and deposits sediment on the opposite bank where water is moving more sluggishly. The thalweg, or imaginary centerline of the river, meanders as well, and with it, the international boundary. The role of rivers as international boundaries is not unique to the United States and Mexico, but rivers as boundaries are less problematic where rivers cut through natural divides such as mountain ranges.

The International Boundary Commission (IBC) was created in 1894 to address the problems associated with the Rio Grande as an international boundary (Timm 1941). The IBC dealt with a wandering international boundary from El Paso to the Gulf of Mexico. In the early history of the IBC, it was common for Rio Grande meanders to eventually detach from the sinuous river channel and produce *bancos*. *Bancos* are the pieces of land associated with oxbow lakes. The ownership of these enclaves was often a contentious issue; each time a new *banco* was formed by the cutoff of a meander, the United States and Mexico were confronted with the implications of gaining or losing of land.

The United States and Mexico signed the 1905 Boundary Treaty to equitably distribute *banco* land to both countries above the LRGV. In 1910 and 1912, *bancos* were allocated in the LRGV (Mueller 1975). The process of assigning bancos was extremely controversial and required years of negotiation. For this reason, the river has since been controlled in such a way that prevents the further creation of *bancos.* The IBC evolved into the International Boundary and Water Commission (IBWC) in 1945. Since then, the IBWC has been confronted with the dual charge of managing the international boundary and allocating the Rio Grande's water (Timm 1941).

Water Demand and Water Control

The population within the Rio Grande basin is growing rapidly in both the United States and Mexico and dependence on the Rio Grande as a resource is growing proportionately. The historical population growth in the United States and Mexico along the border was originally driven by irrigated agriculture (Day 1970), but increasingly border commerce has stimulated the population growth (TNRCC nd). Counter to the steady and increasing demand for water, much of the Rio Grande flows through a desert environment making it a variable, rather than a reliable water source. Three major dams, Elephant Butte, Amistad and Falcon (Figure 1), and many other smaller dams were constructed on the Rio Grande to guarantee a steady water supply for municipal and agricultural purposes and for flood control (Mueller, 1975).

The 1945 Water Treaty specified the amount of water allocated to the United States and Mexico from the Rio Grande and its tributaries. The 1970 Water Management Plan was put in place in the Lower Rio Grande following the severe drought of the 1950s. Unfortunately, the treaty is not well enforced and the management plan is facing difficult challenges in light of the current drought and increasing water demand. Mexico has been accused of violating the treaty by holding more than its share of water behind dams on its Rio Grande tributaries for the past seven years (Swanson 2000). To complicate planning based on water budgets, there are countless unofficial diversion structures and irrigation pipelines that take water from the river system to agricultural lands in the United States and Mexico (Day 1970).

The release of water from the Rio Grande's dams throughout the basin is controlled by the allocation of water rights and the need for water at any given time. The Texas Natural Resource Conservation Commission (TNRCC) is charged with distributing water throughout the Rio Grande basin and struggles with trying to meet a demand that is generally greater than the supply (TNRCC nd). The many dams and diversion structures on the Rio Grande make it less like a free-flowing natural system, and more akin to a municipal pipeline/irrigation delivery device, equipped with valves and connecting distribution pipes. Falcon, Amistad and Elephant Butte Dams serve as valves with their reservoirs acting as holding tanks.

Elephant Butte Dam

The oldest and largest of the dams on the Rio Grande is Elephant Butte, completed in 1916, north of Las Cruces, New Mexico. Prior to the construction of Elephant Butte Dam, the Rio Grande carried sometimes-plentiful Colorado snowmelt to arid West Texas. Since the impoundment of Elephant Butte Dam the Rio Grande is little more than a minor stream when it enters Texas (Mueller 1975).

An IBWC study by Ainsworth and Brown (1933) determined that Elephant Butte Dam had dramatically reduced not only the volume of the Rio Grande's discharge, but also flow variability, since flooding tended to be a seasonable phenomenon prior to the construction of the dam. They also determined that beneath the dam, the release of cold, sediment-poor water (much of the river's silt is contained in Elephant Butte's reservoir), scoured the Rio Grande's channel; more profound changes occurred downstream of the scour zone where reduced discharge and slope caused aggradation. The cross-sectional area of the Rio Grande downstream of El Paso was diminished by 20 to 50 percent between the years of 1917 and 1932 due to aggradation (Ainsworth and Brown 1933).

Ironically, Elephant Butte Dam's capacity to reduce flooding was counteracted by the aggradation that resulted because of the river's inability to transport sediment. Day (1970) actually documented an increase in flooding after the completion of the dam. Channel aggradation in many parts of the Rio Grande downstream of Elephant Butte Dam reduced the river's ability to transmit even relatively small floods without overtopping its banks (Mueller 1975). Furthermore, the lower flow allowed for the encroachment of vegetation on sandbars, in the floodplain, and within the river channel. Vegetation growth in the channel further reduced the velocity of flow and caused sediment to collect and form islands in the channel. Ainsworth and Brown (1933) refer to this phenomenon as "berming."

The non-native species, tamarisk is one of the most prolific and problematic invaders (Mueller 1975). An overgrowth of tamarisk not only traps sediment, but also over-stabilizes banks and floodplains so that the vegetation impedes the river's natural ability to destroy and rebuild its banks and floodplain. The result is further deposition of sediment within the floodplain, a rising of the river bottom, and narrowing of the river's banks (Mueller 1975; Graf 1982). Sediment control dams have been built on the Rio Grande and its tributaries to allay the downstream sedimentation problem.

Still, Ainsworth and Brown's 1933 study found that reduced discharge and the flatter grade of the river's channel produced by aggradation, caused the Rio Grande to become more sinuous both above and below El Paso, Texas. To keep the river from meandering (to preserve the international boundary) and to flush out sediment that had reduced channel capacity, the Rio Grande was canalized, approximately 175 kilometers (110 miles) above El Paso, and rectified 130 kilometers (80 miles) below El Paso, between 1932 and 1943 (Lawson 1936 and 1937; Day 1970). Vegetation clearing and channel dredging are an expensive and necessary part of maintaining the canalized and rectified reaches (Day 1970). The fact that one flood control measure triggered several other projects to maintain the efficacy of the first project, points to the myopia of the initial solution.

The Forgotten Reach

Because of Elephant Butte Dam and municipal and agricultural diversions, little water remains in the Rio Grande when it enters Texas on its way to the "forgotten reach," the area between El Paso and the river's confluence with the Rio Conchos. Benjamin Everitt (1993) studied the effects of anthropogenic alteration of the hydrology of the Rio Grande in a segment of the forgotten reach, between Ft. Quitman and Presidio, Texas. He evaluated this change by examining long-term discharge data, historical aerial photographs and surveys of the river. From these data, he identified stages during which discernible morphological change took place and linked these physical changes to changes in the discharge record.

Everitt found that Elephant Butte Dam, small dams above El Paso, and water diversions, have reduced the flow of the Rio Grande in the Fort Quitman area by 95%. Similar to the findings of Ainsworth and Brown (1933), Everitt concluded that the dam not only reduced the magnitude of discharge, but also the variability. Because of the sparse population in the Fort Quitman area, Everitt did not have to account for many other anthropogenic variables. His study correlated the change in one variable (discharge) to channel aggradation. The reduced discharge rendered the river unable to carry its sediment load and eventually the channel filled-in so that it was only a fraction of its original size. Now the channel is extremely shallow, poorly defined and incapable of conveying floods. When a flood does occur in the forgotten reach, it is not confined to the main channel, the flood flow fans out into many small channels and the international boundary is lost (Everitt 1993).

The Rio Conchos and Amistad Dam

Near Presidio, Texas, downstream of Everitt's study area, the Rio Grande is joined by the Rio Conchos of Chihuahua, Mexico. The Rio Conchos' basin is mostly arid with extremely variable precipitation amounts; therefore, the Conchos is an unpredictable water supply (Day 1970). Much of the water from the Rio Conchos is held within Amistad Reservoir, completed in 1969. Water from Amistad Reservoir is regularly released specifically for use in the LRGV, but much of the water that leaves Amistad Reservoir is diverted for agricultural and municipal purposes before it reaches the LRGV (Mueller 1975).

Of the four dams Mexico has built on the Conchos River, the largest is Boquillas Dam. Boquillas Dam was completed in 1913 and its reservoir has a holding capacity that is ten percent greater than Elephant Butte's (Mueller 1975). In 1968, Mexico completed construction on Luis Leon Dam on the Rio Conchos, further limiting the contribution of the Rio Conchos to the Rio Grande (IBWC 1992). According to Mueller (1975), recharge from the Rio Conchos is what makes the Rio Grande a perennial stream. Now that the Luis Leon Dam has been built, a major drought in the Rio Grande and/or Rio Conchos might cause the Rio Grande to go dry before it reaches Amistad, perhaps through the Big Bend region.

The Lower Rio Grande Valley

The problems of water supply and demand occurring throughout the Rio Grande basin are magnified in the LRGV because this area is one of the fastest growing regions in Texas. In 1940, the population in the LRGV (United States and Mexico) was approximately 150,000. By the 1970s, the population had more than doubled to 500,000 (IBWC 1992). Currently, over two million people live in Texas border counties alone, and several of these counties are projected to be among the fastest growing in Texas (TNRCC nd).

The Rio Grande of the Rio Grande Valley is a low-gradient, meandering river. The term "valley" is a misnomer, because as the Rio Grande passes through Cameron County it flows through a flat delta environment, on its way to Laguna Madre, in the Gulf of Mexico. The LRGV comprises the lower approximately 1,300 square kilometers (500 miles) of the Rio Grande basin's approximately 453,250 square kilometers (175,000 miles) (IBWC 1992). The beginning of what is commonly referred to as the LRGV is marked by the confluence of the Rio Salado with the Rio Grande in Falcon Reservoir (IBWC 1992).

The southernmost counties of Texas: Starr, Hidalgo and Cameron county, comprise the United States side of the LRGV. Because of the region's proximity to the Gulf of Mexico, it receives tropical moisture, often as torrential downpours associated with hurricanes making landfall. Though rain is infrequent, precipitation from tropical storms gives the region the climatic classification of 'humid subtropical' (Mueller 1975), with approximately 64 centimeters (25 inches) of rain per year (TNRCC nd).

Flood Control in the Lower Rio Grande Valley

The anthropogenic activities occurring in the upper parts of the Rio Grande have an indirect effect on the morphology of the river in the LRGV. Upstream demand and withdrawal of water has lessened the amount left flowing through the LRGV. What follows here is a summary of events occurring in the LRGV that more directly influenced the morphology of the Rio Grande there. The motivation behind the alteration of the natural hydrology of the Rio Grande in the LRGV has been water storage and flood control. Flood control planning in the LRGV has evolved with each major flood. A detailed account of the history of flood control in the LRGV is given here to provide a context for morphologic change. Major flood events described in this section, are identified by discharge peaks on the hydrograph (Figure 3).

The LRGV experienced a major flood in 1904 that instigated the first serious consideration of flood control, but a lack of resources stalled an organized campaign until the next major flood that occurred in 1909 (Water Conservation Association of the Lower Rio Grande Valley 1951). In the aftermath of this flood, the Hidalgo County Drainage District was formed. Then in 1919, the Cameron and Hidalgo Counties Drainage and Flood Protection Association was created after the next major flood. Following a storm event in June of 1922 that generated a 4,144 cubic meters per second (cms) (148,000 cubic feet per second (cfs)) flood crest near Rio Grande City, a Flood Control Report was completed in 1923. This report made recommendations for the construction of floodways and flood diversion structures.

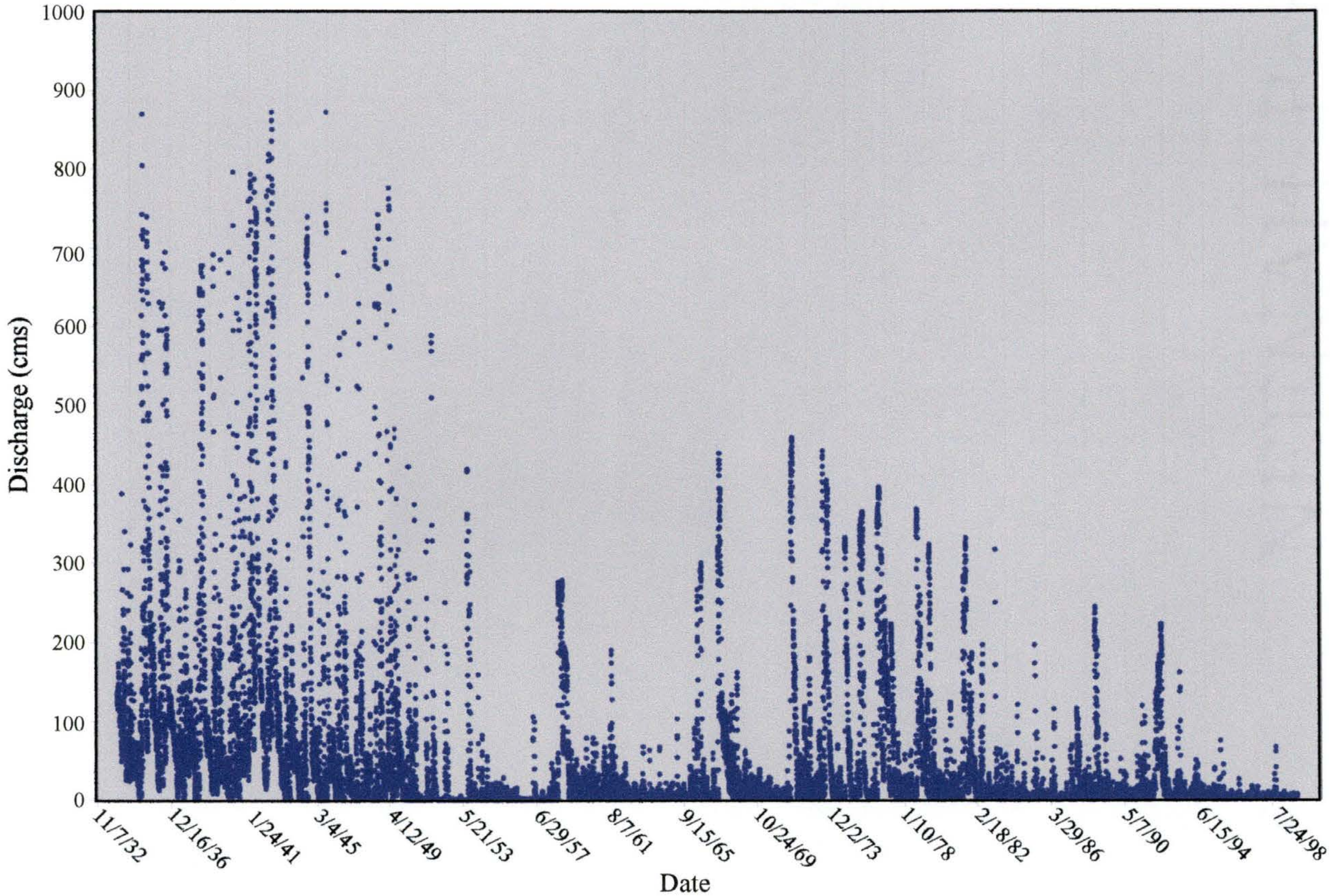

Fig. 3. Hydrograph of Mean Daily Discharge versus Time

Several years were spent designing the floodways and negotiating the bond issues to pay for the massive undertaking (Water Conservation Association of the Lower Rio Grande Valley 1951). In 1926, the operation and design of the floodway system was decided and construction began. Of the 3,360 cms (120,000 cfs) of the design flood, 1,960 cms (70,000 cfs) would be diverted to the Arroyo Colorado and 1,400 cms (50,000 cfs) would be diverted to the North Floodway (1951).

In 1930, interest in flood control and storing floodwaters was renewed by the Depression and its focus on reclamation projects. The Rio Salado, a tributary that carries runoff from the Mexican state of Nuevo Leon, enters the Rio Grande through Falcon Reservoir. It has historically made significant contributions to the Rio Grande's discharge (Mueller 1975), but in 1930, much of the Rio Salado's recharge was withheld when Carranza Dam was completed in Mexico. The need for more control of floodwaters in general, and diversion dams in particular, was reinforced by the occurrence of a major flood in September 1932 which failed to be controlled by the existing floodway system. It was recognized at this time that historical floods in the LRGV, with discharges ranging from approximately 2,800 to 5,600 cms (100,000 to 200,000 cfs), could not be accommodated by the capacity of the Rio Grande channel at Brownsville. At that time the capacity of the river was estimated to be approximately 840 cms (30,000 cfs) (Water Conservation Association of the Lower Rio Grande Valley 1951).

Because of the persistent threat of seasonal flooding, and the propensity of the Rio San Juan and other Mexican tributaries to deliver flood waters to the region, the Lower Rio Grande Flood Control Project was approved in 1932 by the United States and Mexico (IBWC 1951). Figure 4 illustrates the main components of the flood control system.

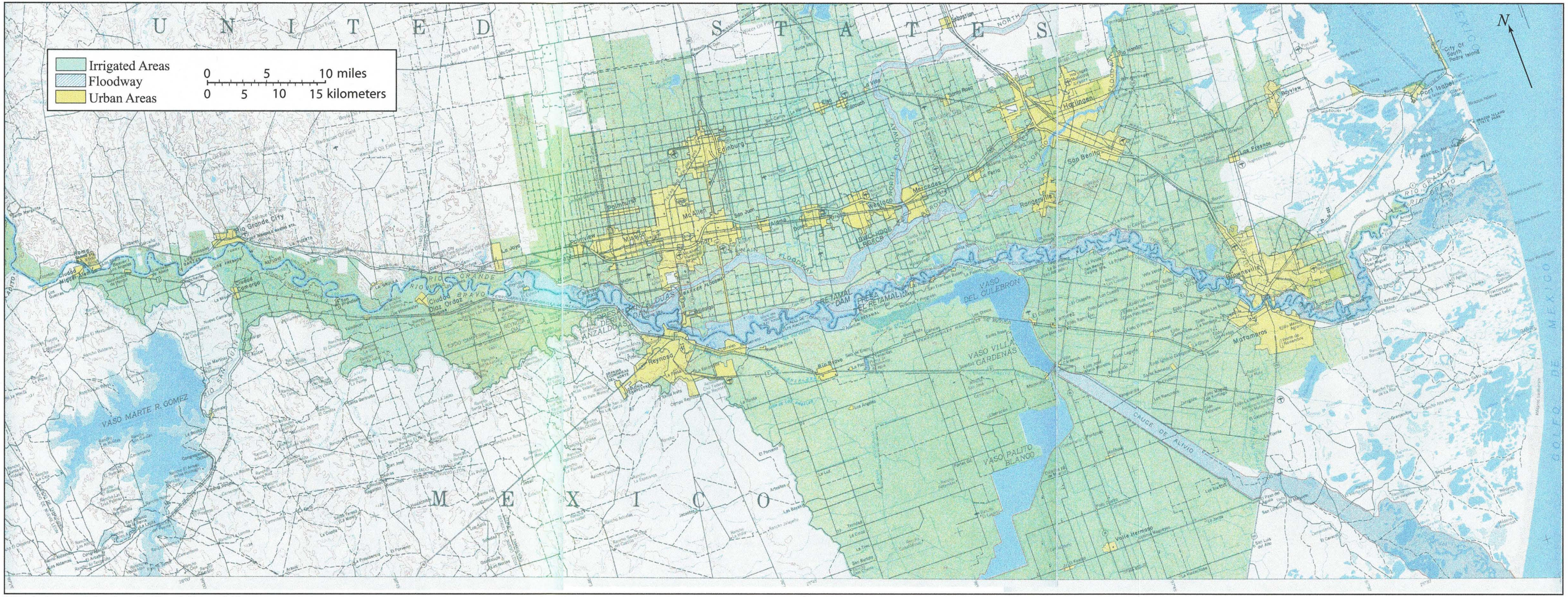

Fig. 4. Lower Rio Grande Flood Control System
Modified from IBWC map: Lower Rio Grande Valley, United States and Mexico, Flood Control Works and Irrigation Developments, date unknown

The project was a massive undertaking that utilized existing diversion structures and dams and levees, but it also called for the construction of many more flood-control structures (IBWC 1992). The project, which incorporated the Rio Grande's channel and the construction of artificial channels to the north, also created approximately 164 kilometers (102 miles) of new levees on both sides of the river. The floodway system begins just south of the border of Starr and Hidalgo counties. The southern "floodway" contains the Rio Grande (Figure 5). The Main Floodway branches into the North Floodway (Figure 6) and the Arroyo Colorado floodway.

After reconciling the disagreements arising from how to determine what would constitute an equitable distribution of floodwaters in the United States and Mexico, in 1932, two diversion structures were agreed upon. These structures would be completed in the future, but the plans were laid out in 1932 for Anzalduas and Retamal Dams to regulate the flow of water into the floodways (IBWC 1992). Anzalduas Dam was completed south of Mission, Texas to control floodwaters entering United States and Mexican floodways, and Retamal Dam was completed south of Donna, Texas, to control floodwaters entering Mexican floodways.

The Lower Rio Grande Emergency Flood Control Project, a federal bill, was passed in 1935. The bill, and subsequent appropriation acts, ensured that the flood control projects would be federally managed. Federal funding and acquisition of land allowed for the building of levees along the floodways in both the United States and Mexico (Water Conservation Association of the Lower Rio Grande Valley 1951). In addition, Congress gave the United States permission to build revetments, retaining walls and other structures to maintain the integrity of the banks of the river and the walls of the floodways.

Fig. 5. Photograph of the Rio Grande downstream of Brownsville, Texas

Fig. 6. Photograph of the Main Floodway near Mercedes, Texas

In 1937, Mexico built the Retamal Intake and Canal, and Azucar Dam on the Rio San Juan. Then, the Marte Gomez Dam was completed on the Rio San Juan in 1943. The dams help to contain floodwaters, but they also hold back water that once contributed to the total discharge of the Rio Grande (IBWC 1992).

The need for international management of the Rio Grande and its tributaries for flood control was becoming dire. In 1940, Federal Project No. 5 was passed to provide for the maintenance of existing floodways. It also paved the way for the storage of floodwaters in reservoirs within the main stem of the Rio Grande in the future. The project specified how much water would be diverted throughout the different segments of the existing floodway system and also improved the system by mandating the building of hundreds of kilometers of new levees and floodways in the United States and Mexico.

In 1954 Falcon Dam was completed near the Zapata/Starr county line, just in time for one of the largest floods in gaged history to occur in the Rio Grande basin. Historical maximum discharges were recorded at gaging stations on the Rio Grande at Del Rio and Laredo. Falcon Dam captured approximately 2,281,050,000 cubic meters (1,850,000 acre-feet) of this floodwater and spared the Lower Rio Grande from major damage (IBWC 1992).

Though Falcon Dam is able to hold a substantial portion of Rio Grande floodwaters from the middle and upper portions of the Rio Grande's basin, downstream of Falcon Dam, near Rio Grande City, the Rio San Juan has historically delivered its own floodwaters to the Rio Grande. Dams constructed on the Rio San Juan have moderated both the positive and negative impacts of this tributary on the Rio Grande; they have prevented flooding, but they have also deprived the river of recharge.

In September and October of 1958, tropical storms produced flooding in the Rio Conchos and Rio San Juan basins which again generated large amounts of precipitation that lead to flood releases from Falcon Dam (IBWC 1992). Falcon Dam and the floodway system attenuated the effects of this flood such that only 356 cms (12,700 cfs) of the 2,912 cms (104,000 cfs) measured at the Rio Grande City gaging station, were measured at the Brownsville gaging station. However, even this fraction of the discharge produced flooding because of the diminished conveyance capacity of the main channel of the Rio Grande and its floodways. During this flood event, the capacity of the Rio Grande's channel at Brownsville was estimated to be about 67% of what it was before major flood control initiatives (IBWC 1992). A study by the IBWC (1992) attributed this loss in conveyance capacity to sedimentation and the encroachment of vegetation in the Rio Grande's main channel and floodways.

After the tropical storms of 1958, damages to the floodway system were repaired (IBWC 1992). To restore channel capacity in preparation for future flood events, the IBWC cleared vegetation in the United States and Mexico from the river, up to the river's bank, or as far as approximately 100 meters (330 feet) from the water's edge. This ambitious task was completed in 1962. Small floods that occurred during the clearing process made it evident that vegetation removal would have to be an on-going process to preserve the capacity of the floodways (IBWC 1992).

Hurricane Buelah stalled over the LRGV in September of 1967 and produced enough precipitation in the Rio San Juan's basin that its reservoir at Marte R. Gomez Dam filled to its 937,080,000 cubic meters (760,000 acre-ft) capacity. The hurricane also generated a maximum peak discharge at Rio Grande City of 5,880 cms (210,000 cfs), an amount approximately 50% greater than the Lower Rio Grande Flood Control Project was designed to convey (IBWC 1992). As a consequence, the main channel of the Rio Grande and the floodways were severely flooded, and again, major repairs were necessary for the floodways to recuperate from the deluge. Additional improvements were made to the flood-control system including more vegetation clearing.

The 1970 Boundary Treaty encouraged the United States and Mexico to actively preserve the international boundary by continuing to clear vegetation and by building levees. The Treaty also allowed for channel dredging and excavation and bank enhancement with revetments (IBWC 1992). The International Boundary and Water Commission regularly erects and maintains revetments along the river in the United States and Mexico to counteract natural bank erosion. Revetments take many forms, but are most typically wire-meshed nets and/or large rock pieces. Both serve the purpose of galvanizing the river's banks (Day 1970). No map shows the specific locations of revetments on the Rio Grande, but Figure 4 illustrates the areas in which they are allowed to be constructed (in the floodway zones and along the river).

Following the 1970 Boundary Treaty, more levees were constructed in the Brownsville area, approximately 45 meters (150 feet) from the center of the Rio Grande in the United States and Mexico. The total length of levees in the flood control system grew to approximately 485 kilometers (300 miles) in the United States and approximately 240 kilometers (150 miles) in Mexico (Day 1970). Levees have historically allowed for the settlement of the Rio Grande flood plain in the LRGV, but according to a 1992 IBWC report, irrigated farming has decreased along areas of the river since the 1970's. The 1965 Border Industrialization Program, commonly known as the Maquiladora Program, and the

North American Free Trade Agreement (NAFTA) (TNRCC nd) have encouraged the shift in land use from agricultural to industrial. Still, for much of the century, agricultural land use within the floodplain was predominant (Day 1970).

After the completion of Falcon Dam, occupation of the flood plain for cultivation was especially widespread (IBWC 1992). Both agricultural and urban land uses have dramatically decreased the amount of native vegetation (including riparian vegetation) in the LRGV and have, in turn, altered the morphology of the river (Chapman, Popoulias and Onuf 1998). Due to a long history of clearing of native vegetation to make land suitable for cultivation, by 1988 95% of Tamaulipan brushland in the LRGV had been cleared (Chapman, Popoulias and Onuf 1998).

Furthermore, the IBWC regularly dredges the Rio Grande and mows vegetation between the river and the artificial levees. This process of mowing indiscriminately rids the floodplain of both non-native and native vegetation. There has been a movement against the IBWC's attempts to maintain the floodways by groups that believe boundary preservation is not worth the cost of the destruction of riparian habitat.

The United States Fish and Wildlife Service (USFWS) is purchasing land along the Rio Grande's riparian zones and building the Rio Grande Valley Wildlife Corridor. Their intention is to return the riparian zone to its wild state for the sake of preserving habitat for endangered species such as the rare jaguarundi (Felis yagouaroundi). The increasing trend of private ownership of stretches of riparian zones has successfully kept it from IBWC management. The initiative had amassed 25,000 hectares by 1998 and continues to acquire more land (Chapman, Popoulias and Onuf 1998). The Rio Grande Valley Wildlife Corridor Project is seeking to restore parts of the river to a natural state, but it is a relatively new endeavor. A century of water control initiatives have taken their toll on the river in the LRGV.

Ainsworth and Brown (1933) studied the downstream effects of Elephant Butte Dam on the Rio Grande near El Paso, and Everitt (1993) studied these effects in the forgotten reach. Even though there has been a dramatic alteration of the morphology of the Rio Grande's channel in the LRGV, there has been little quantitative research done to measure this change. The first real evaluation of changes in channel morphology in the LRGV was done by Day (1970). He used a series of aerial photographs from 1934, 1947 and 1960 to measure changes in the Rio Grande's channel width. Day used photo-mosaics of the aerial photographs and took 10 randomly spaced measurements of channel width, using "permanent vegetation along the river bank" as the beginning and stopping point of each measurement.

The results of his analysis indicate that there was little change between the photos taken in 1934 and 1947, the period prior to the completion of Falcon Dam in 1954, but marked change between 1947 and 1960. Day attributes channel shrinking to decreases in water supply due to the construction of Falcon Dam and the Lower Rio Grande Flood Control Project. The small number of measurements over approximately 260 kilometers (160 miles) of the river, make it difficult to accurately quantify the amount of change, however. The use of 1960 aerial photographs to measure post-dam change is also inadequate, because the river's responses to change likely took longer than 6 years. In addition, the use of what Day calls "permanent vegetation" to measure channel width is extremely problematic. What constitutes permanent vegetation? There are parts of the channel whose banks are not bound by vegetation at all. Furthermore, this chapter has detailed a long history of vegetation clearing by the IBWC which undermines the use of "permanent vegetation" as a measuring point. Still, Day's study is valuable in that it shows a trend of channel narrowing which implicates water control measures.

The following chapter describes the methods used in this thesis to quantify channel change using GIS. These methods overcome the shortcomings of Day's 1970 work and attempt to provide a more reliable, quantitative assessment of morphologic change. The Results and Conclusions chapter discusses in more detail the implications of the hydrologic control measures described in this chapter on the morphology of the Rio Grande downstream of Brownsville.

CHAPTER 4

METHODOLOGY

The use of aerial photographs and historical maps to study changes in river morphology over time is a well-established tradition. Unfortunately, a limitation of this practice has always been that the results were qualitative, rather than quantitative. The application of Geographic Information Systems (GIS) to the task of evaluating geomorphic change, generates data that are more quantitative. The GIS methods used in this study are explained in this chapter. First, the process of historical research pertaining to flood control and river modification is described. Next, the attainment and use of discharge data are discussed, and then the application of GIS and graphic design programs to process maps and aerial photographs for quantitative measurements will be covered.

Historical research

Historical literature and documents pertaining to events that impacted the study reach of the river were researched to put the physical changes of the river in the context of human history. The need for a historical component to this work was immediately evident because human settlement and actions have had a dramatic impact on the river.

Significant historical events were correlated with marked changes in discharge. Anthropogenic activities such as dam building, settlement, and irrigation were evaluated in terms of changes in the river's morphology.

Historical data were obtained from the IBWC headquarters office in El Paso, Texas and the IBWC Lower Rio Grande field office in Mercedes, Texas. The Center for American History at the University of Texas at Austin was also a valuable source of historical data and maps.

Discharge Data

Continuous, mean daily discharge data from a gaging station downstream of Brownsville, Texas were used to quantify the amount of water entering the study reach. The gaging station is owned and operated by the IBWC. Mean daily discharge data from January 1, 1934 to Dec 31, 1999 were used for this study. The mean daily discharge data was downloaded from the IBWC web site and imported into an Excel spreadsheet. A hydrograph was created by plotting mean daily discharge versus time (Figure 3). Correlations were drawn between major water control initiatives and changes in discharge. This information is presented in Chapter 5.

Historical Maps and Aerial Photographs

The study reach of the Rio Grande below Brownsville was analyzed at three points in time: 1995/96, 1950 and 1911. The methodology described below is the crux of this thesis. The three time periods of study were selected for the following reasons. Follett's 1911 topographic survey of the Lower Rio Grande Valley predates the construction of major water control structures and large-scale agricultural water diversion in the Rio Grande basin, and therefore, represents the river in a near-natural state. The 1950 aerial photographs were selected for their useable scale (one that allows for good resolution of detail) and more importantly, because they were taken prior to the construction of Falcon Dam. The 1995/96 Digital Ortho Quarter Quads (DOQQs) were chosen because they are the most recent aerial photos available of the area, and their digital format and one-meter resolution are conducive to resolving and measuring river features.

Rather than qualitatively comparing three views of the river, from different sources, taken at different times, this work uses GIS to manipulate three different media: DOQQS, aerial photographs and photographic reproductions of a 1911 topographic survey of the LRGV. Using GIS, all three media were put into the same geographic space for the purpose of making quantitative, rather than qualitative, comparisons with assurance. Once all of the images were in digital format and geographically referenced, river features were overlapped and compared, and the degree of change was quantified. Because each of the three views of the river is from a different source, different processing steps were required before they could be brought together and compared.

1995/96 DOQQs

Six DOQQs, taken in 1995/96, covered the study area (Figure 7). These photographs are available as digital images on compact disks and were obtained from United States Geological Survey (USGS). The DOQQs were easily tiled together using the GIS program ARC/INFO because they are georeferenced to the surface of the Earth and have a known projection. This means that the program “knows” to draw the images so that they line up because of the geographic information inherent to the image. For this reason, it was logical to begin the GIS processing work with the most recent data set. The 1995/96 aerial photos from which the DOQQs were created were taken by the National Aerial Photography Program at a scale of 1:40,000.

Some of the aerial photographs originally taken in 1995 did not meet quality control requirements necessary to process them into DOQQs, so they were photographed again in 1996. Not accounting for variations in discharge (river flow conditions might have been drastically different during the two aerial photography missions that photographed the river) could have presented a problem for this study. Fortunately though, differences in discharge between the two dates are negligible, making measurements of wetted-channel width comparable. Still, because the window of acceptable quality is fairly wide for processing DOQQs, some of the images are much darker and/or more saturated in color than others (Figure 7). These differences made image interpretation more difficult, but they were not severe enough to seriously hinder the process.

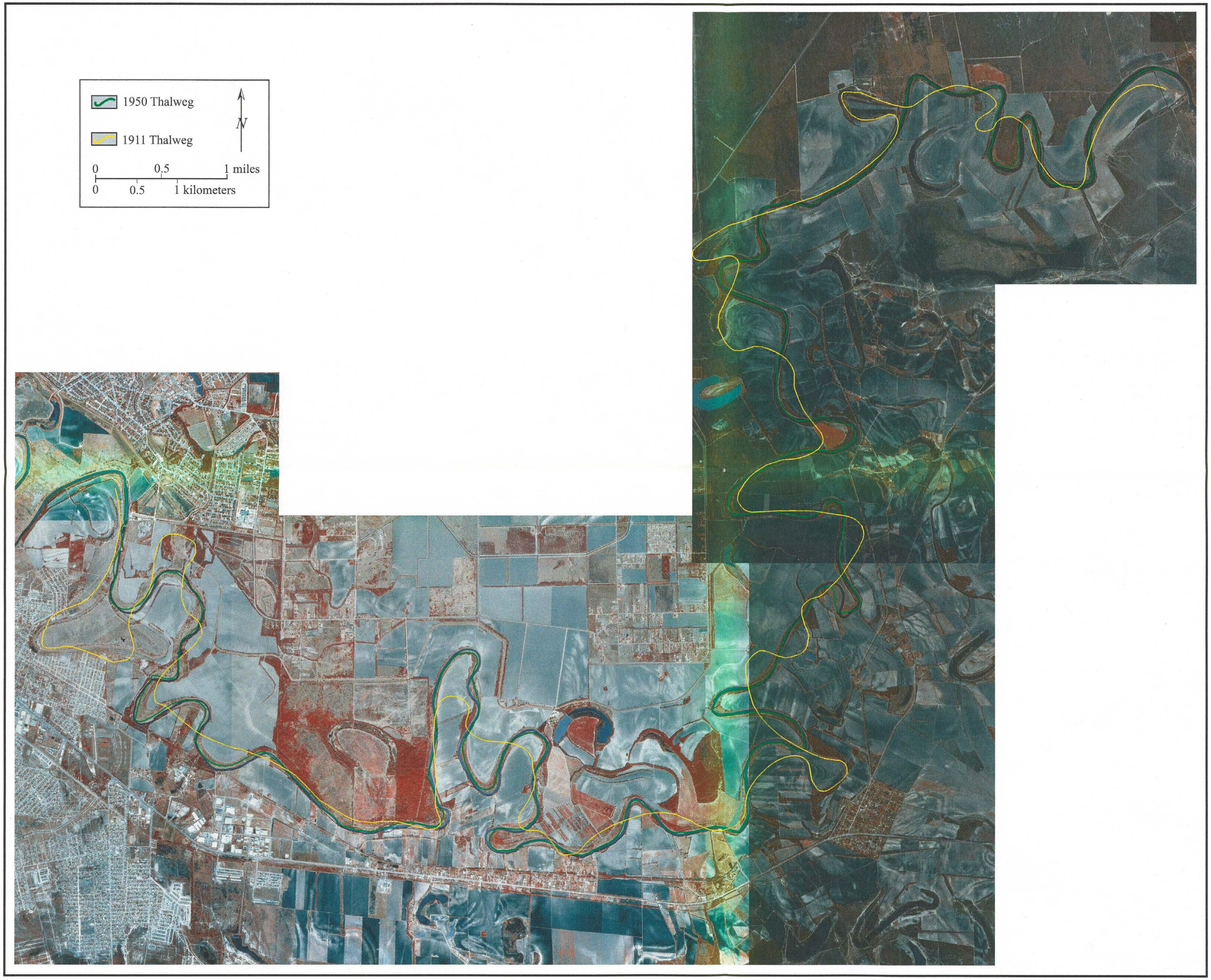

Fig. 7. Mosaic of 1995/96 Digital Orthophoto Quarter Quads of the Rio Grande Downstream of Brownsville, Texas Showing Overlays of 1950 and 1911 Thalwegs

1950 Aerial Photographs

To capture the greatest contrast in the state of the river prior to and after the construction of Falcon Dam in 1954, aerial photographs taken in 1950 were used. The 1950 aerial photos were taken by the Soil Conservation Service at a scale of 1:20,000 and were acquired from the Texas Natural Resources Information System (TNRIS). Eight photos, approximately nine by nine inches in size, were needed to cover the length of the study reach (Figure 8).

The 1950 aerial photographs are not referenced to the surface of the earth like the 1995/96 DOQQs. The 1950 and 1995/96 photos also have different scales. Because the DOQQs are already georeferenced, it was logical to reference, or match the aerial photographs to them.

First, the eight 1950 aerial photographs were scanned so they were available in digital format. Next, the borders of the photos were eliminated, making it possible for the photos to be made into a mosaic. This was done using the 'Grid' command in ARC/INFO, which provides the tools for the creation of a sizable (scaleable) box. When the box is sized on the photo so that it is positioned just inside the border, it is used as a "cookie cutter" that removes the border, leaving the photo inside.

Once the borders were removed from the scanned aerial photos, they could have been tiled together into a mosaic using a graphic design program, by grabbing and dragging the images together. While this process would serve the purpose of connecting the aerial photos, it does not put them in the same scale as the DOQQs; the creation of a

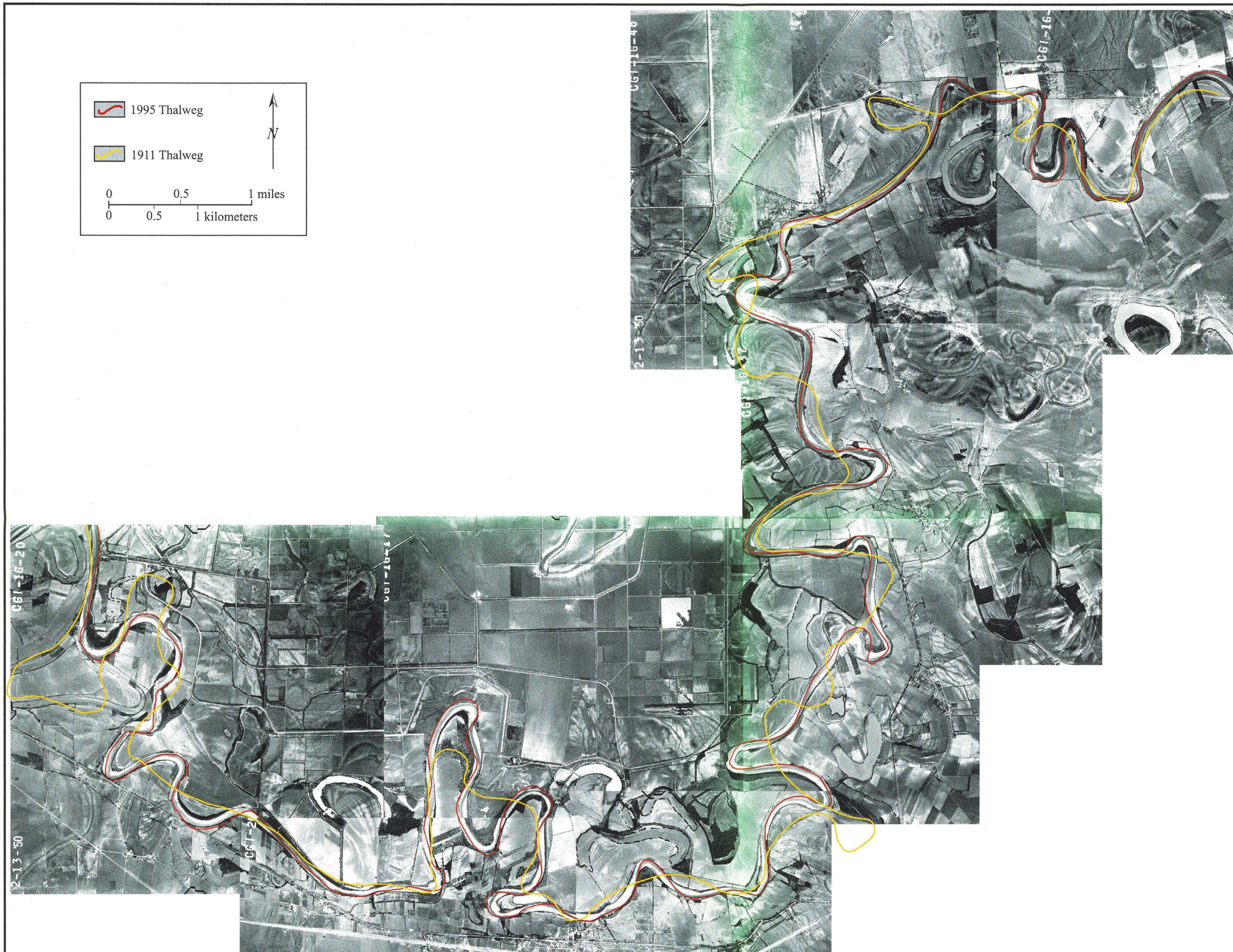

Fig. 8. Mosaic of 1950 Aerial Photographs of the Rio Grande Downstream of Brownsville, Texas Showing Overlays of 1995/96 and 1911 Thalwegs

simple mosaic does not accomplish the goal of putting the two sets of images in the same geographic space either. Further processing steps were necessary.

Using identifiable, distinct points, like the intersections of major roads, present and visible on both sets of imagery, the aerial photos were "referenced" to the DOQQs and their underlying geographic coordinate system. A minimum of four match points was required on each aerial photo, as close to the corners as possible, to successfully reference them to the DOQQs. More than four match points were used when possible. Because of the lack of population, and therefore paucity of cultural features along some sections of the river, (especially on the Mexican side) it was difficult to find good match points on some of the aerial photographs. In some cases, dirt roads had to be used which was problematic because they are not permanent, reliable features.

Tic marks were created on the aerial photos and the DOQQs at each match point by drawing corresponding points with ARC/INFO tools. Using the underlying geographic coordinate system of the DOQQs, the x and y coordinates of the tic marks given on the DOQQs were assigned to the corresponding tic marks on the aerial photos. Each individual aerial photo was then rectified or "rubber-sheeted" using ARC/INFO's Warp/Registration tools. When tic marks did not match well (when dirt roads were used, for example), the rubber-sheeting process produced a distorted image. The root mean square (RMS) error, a statistical calculation that evaluates the effectiveness of tic registration, was used to gauge the reliability of the match process. When an accurate registration was achieved, a mosaic of the aerial photographs was generated in ArcInfo in the same scale as the DOQQs.

1911 Topographic Survey

Like the 1950 aerial photographs, the 1911 Follett topographic survey of the Lower Rio Grande Valley (Figure 9) was not georeferenced to the surface of the Earth. The survey was divided into plates that were folded and bound in a publication that had weathered with age (IBWC 1913). Because of the fragile condition of the plates, photographic reproductions were made. Each plate was photographed under a sheet of glass with the scale shown clearly. Four plates were needed to cover the study reach.

The intersections of roads and/or cultural features could not be used to reference the 1911 topographic survey plates to the DOQQs because of the lack of match points. Though there was some settlement of the floodplain at this time, it was markedly different than the pattern in 1995/96. Furthermore, the 1911 topographic survey is in the form of a paper map, not aerial photographs, making it even more difficult to be certain of match points. Modern, digital U.S. Geological Survey 1:24,000 scale, topographic maps were used to georeference the 1911 survey. Distinct topographic points such as the tops of hills and benchmarks were used to match the 1911 survey to the modern topographic quadrangle (quad) maps when roads or other cultural features were not available. Because the digital quad maps are in the same geographic projection as DOQQs, registering an image to a digital quad map is analogous to registering it to its corresponding DOQQ. However, it was necessary to use a graphic design program to create a mosaic of the 1911 survey plates.

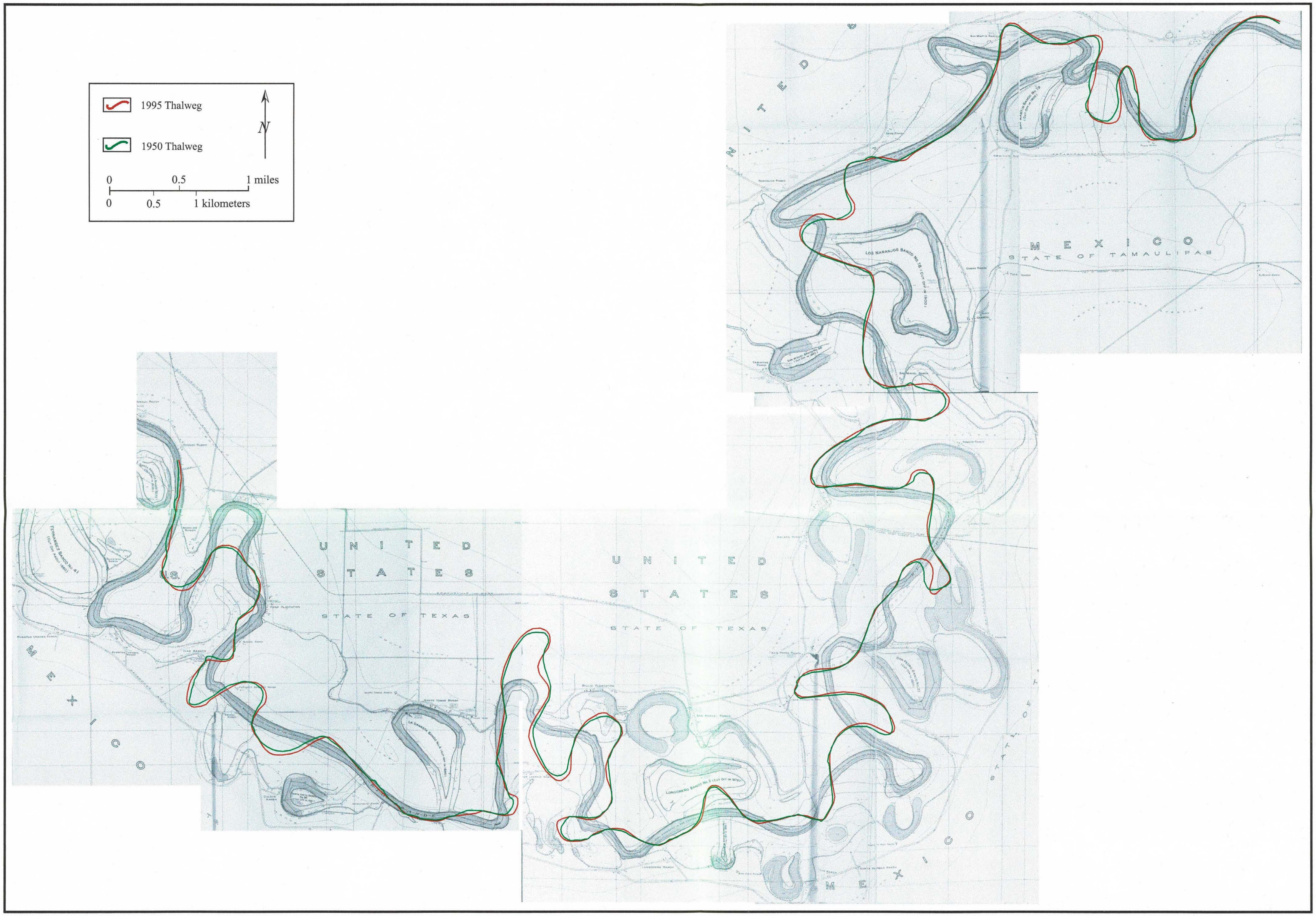

Fig. 9. Mosaic of Photographic Reproductions of Follett's 1911 Topographic Survey of the Lower Rio Grande Valley, Texas Showing Overlays of 1995/96 and 1950 Thalwegs

Digitizing River Features

Once all of the imagery was "in the same space," river features were digitized and made into GIS coverages. The 1995/96 DOQQs and the scanned 1950 aerial photographs were digitized using a mouse to trace river features on a monitor screen, while the 1911 survey was digitized with the keypad's crosshairs following the river on a digitizing table. The thalweg (deepest part of the river where water tends to move the fastest) and the left and right riverbanks were digitized for each year. In addition one hundred perpendicular-to-flow transects were drawn on all three sets of imagery from bank to bank and used to measure wetted channel width. The arcs were then selected in ARC/INFO and the channel width queried.

Once all of the data were collected from each of the three sets of imagery, Adobe Illustrator was used to produce finished maps. Scales and legends were added and the three maps were sized to facilitate easy comparison. The mosaic maps for each period of study are presented as Figures 7, 8 and 9.

CHAPTER 5

RESULTS AND CONCLUSIONS

Reduced Magnitude and Variability of Discharge

The dramatic decreases in discharge volume and variability at the Brownsville gaging station are clearly evident from the hydrograph of mean daily discharge versus time (Figure 3). The Brownsville gage is located downstream of the major water control structures on the Rio Grande (Figures 1 and 2). A comparison of the discharge before and after the construction of Falcon Dam in 1954 shows a pronounced decrease after dam construction. Prior to 1954, the highest three mean daily discharge measurements recorded at the Brownsville gaging station were approximately: 862 cubic meters per second (cms) (30,800 cfs), occurring September 14, 1942, 859 cms (30,700 cfs), occurring October 18, 1945, and 859 cms (30,700 cfs), occurring June 10, 1935. After the construction of Falcon Dam, the highest three mean daily discharge measurements were approximately: 454 cms (16,200 cfs), occurring October 18, 1971; 437 cms (15,600 cfs), occurring July 7, 1973; and 434 cms (15,500 cfs), occurring October 1, 1967.

Though there appears to be a transition in the character of discharge evident from the hydrograph that occurs around 1954, it would be an oversimplification to look only at Falcon Dam when searching for the cause of discharge reduction. The impact of Amistad

Dam (completed in 1969) is likely expressed by lower discharge peaks in the hydrograph as well, although it is difficult to separate the effects of Amistad and Falcon Dam since their influences overlap. Luis Leon Dam was also completed on the Rio Conchos in 1968, one year before Amistad.

Unfortunately, the discharge record for the Brownsville gaging station does not extend far enough back in time to quantify how much discharge decreased in the LRGV when Elephant Butte was completed in 1916. The impact of Elephant Butte Dam on discharge in the Rio Grande Basin was discussed in Chapter 3. The amount of water reaching the LRGV from the upper part of its basin is difficult to quantify. South of El Paso, the Rio Grande becomes a losing stream as it flows through the desert before it reaches the Brownsville gaging station. Though the amount cannot be easily quantified, it is reasonable to assume that Elephant Butte Dam either directly and/or indirectly contributes to discharge reductions in the LRGV.

Elephant Butte Dam was not the only major water control initiative that predated the Brownsville discharge record. Boquillas Dam, with a reservoir capacity larger than Elephant Butte's, was completed on the Rio Conchos in 1913, and in 1930, Carranza Dam was completed on the Rio Salado, a tributary of the Rio Grande in the LRGV. In addition, construction of the floodway system began in 1926 in the LRGV. The details of the construction and impacts of these and other hydrologic control initiatives are discussed in more detail in Chapter 3.

The Brownsville gage began recording discharge in 1934, a time when dam construction and water control initiatives were widespread. Though the Brownsville gaging station record is one of the longest and most complete records of Rio Grande discharge, the record does not predate all major water control initiatives on the Rio Grande and its tributaries. The largest discharge events were not recorded, but they were estimated. Before the construction of the Brownsville gage, flood flows estimated at 2,800 to 5,600 cms (100,000 to 200,000 cfs), occurred in the LRGV (Water Conservation Association of the Lower Rio Grande Valley 1951).

Hydrologic control measures on the Rio Grande have not only reduced the volume of discharge recorded at the Brownsville gage, but also the variability of discharge. Not only were peak flows reduced after the implementation of hydrologic control measures, periods of zero or low flow, were reduced as well. During the extremely dry years of 1952 and 1953, there were spans of time when no discharge (zero) was recorded at the Brownsville gage. Other seasonal droughts resulted in zero discharge measurements in the early period of the hydrograph.

Since the construction of major dams on the Rio Grande and its tributaries, discharge has been modulated so that no flow or extremely low flow is a rare occurrence. Steady low flow has become the norm, instead of high fluctuation seasonal flow. After the construction of dams and other water control initiatives, flood peaks associated with tropical precipitation occur on the hydrograph, but the peaks are smaller than historical flood peaks. The alteration of the magnitude and variability of the discharge record has made discharge in the LRGV less geomorphically effective. This will be further discussed later in this chapter.

Evidence of Channel Narrowing

One hundred channel width measurements for each time period of evaluation were made (Table 1). To facilitate the comparison of minimum and maximum channel widths, the measurements were sorted in ascending order. The minimum width of the river in the study reach for 1911 was approximately 60 meters (197 feet); the minimum width of the river in 1950 was approximately 13 meters (43 feet); the minimum width of the river in 1995/96 was approximately 15 meters (49 feet). The maximum width of the river in the study reach for 1911 was approximately 137 meters (450 feet); the maximum width in 1950 was approximately 128 meters (420 feet); the maximum width in 1995/96 was approximately 65 meters (213 feet). The fact that the minimum width of the river in 1911 is comparable to the maximum width in 1995/96 illustrates how much the river has narrowed.

It is more telling to include the percent of change when comparing the average channel widths of the river over time. From 1911 to 1995/96, the average width of the river in the study reach decreased by approximately 54 meters (177 feet), a reduction of approximately 61%. From 1911 to 1950, the average channel width decreased by approximately 35 meters (115 feet), a reduction of approximately 40%. From 1950 to 1995/96, the average channel width decreased by approximately 18 meters (59 feet), a reduction of approximately 35%. The reasons for the dramatic reductions and the consequences, are discussed in 'The Rio Grande Out of Equilibrium' section at the end of this chapter.

Table 1. Width of the Rio Grande Downstream of Brownsville in 1911, 1950 and 1995/96

	Wetted Channel Width (meters)				Wetted Channel Width (meters)		
Transects*	1911	1950	1995/96	Transects	1911	1950	1995/96
1	59.9	13.2	15.2	51	84.4	51.7	33.7
2	60.0	14.8	15.7	52	85.0	52.2	34.0
3	61.8	16.1	17.3	53	85.9	52.8	34.6
4	61.8	17.3	18.1	54	86.6	53.1	34.8
5	62.3	18.0	20.1	55	87.0	53.2	35.2
6	64.3	19.1	20.3	56	87.2	57.9	35.6
7	65.4	20.6	20.8	57	87.4	58.6	35.9
8	66.6	21.1	21.1	58	87.6	58.6	36.0
9	66.8	24.9	21.4	59	88.0	58.9	36.2
10	68.1	25.1	22.2	60	88.3	59.0	36.2
11	68.8	25.3	22.8	61	88.6	61.1	36.2
12	70.3	26.0	22.9	62	89.4	62.6	36.6
13	70.7	26.2	23.2	63	92.0	62.7	36.6
14	72.0	26.8	23.3	64	93.5	63.3	36.9
15	72.1	27.6	23.5	65	93.7	63.3	37.2
16	72.3	28.6	23.9	66	93.7	64.4	37.5
17	73.6	29.4	24.8	67	94.0	64.4	37.8
18	74.0	30.3	24.9	68	94.3	64.8	38.4
19	74.5	30.4	25.0	69	94.9	65.0	38.8
20	74.6	30.4	25.6	70	96.2	65.8	39.5
21	75.1	30.8	26.0	71	96.5	67.0	39.6
22	75.8	31.8	26.0	72	97.0	67.6	39.8
23	76.5	32.8	26.2	73	98.5	67.7	40.0
24	76.7	32.9	26.8	74	99.2	69.1	40.0
25	77.4	33.0	27.3	75	99.3	69.5	40.3
26	77.6	33.2	27.4	76	99.3	70.3	40.4
27	78.2	33.2	27.5	77	99.5	70.5	41.3
28	78.4	33.5	27.8	78	99.8	70.5	41.6
29	78.6	33.7	28.1	79	100.3	70.5	42.1
30	78.9	34.1	28.2	80	100.4	71.0	42.1
31	79.1	34.4	28.4	81	100.6	71.3	42.7
32	79.3	35.7	28.6	82	100.7	72.1	43.1
33	79.4	37.0	28.6	83	101.6	74.0	43.3
34	79.7	37.9	29.2	84	103.3	74.3	44.1
35	79.9	38.0	29.3	85	103.8	75.1	44.6
36	80.2	39.2	29.5	86	103.9	75.1	45.3
37	80.8	40.0	29.5	87	105.2	75.2	46.0
38	80.8	40.2	30.0	88	105.3	76.1	47.1
39	80.8	40.9	30.1	89	105.6	82.2	47.3
40	80.8	42.6	30.3	90	105.7	83.6	47.4
41	81.4	43.3	30.3	91	107.4	86.5	47.6
42	82.0	44.1	30.9	92	108.1	86.9	48.3
43	82.6	44.7	31.4	93	109.3	87.1	48.6
44	82.8	46.0	31.9	94	110.1	88.7	49.1
45	82.8	46.1	32.2	95	122.4	88.8	49.8
46	82.8	47.6	32.8	96	122.5	97.3	53.9
47	82.9	48.9	32.8	97	127.4	102.2	55.0
48	83.5	49.0	32.8	98	129.8	102.4	58.0
49	84.0	49.6	32.9	99	130.3	110.9	60.2
50	84.1	50.6	33.2	100	136.9	128.0	65.1
*Sorted in ascending order			Average width of transects:		87.9	52.8	34.4

Evidence of a Lower Capacity, Meandering River

Downstream of Elephant Butte Dam, Ainsworth and Brown (IBWC 1933) found that aggradation which resulted from reduced discharge, caused the Rio Grande to become more sinuous. Measurements of thalweg length in the LRGV show the same result. The thalweg in 1911 was 46,766 meters (153,432 feet) long. In 1950 it was 49,917 meters (163,770 feet) long, and in 1995/96 it was 51,472 meters (168,871 feet) long. From 1911 to 1995/96, the Rio Grande thalweg gained 4,706 meters (15,440 feet) of length, a growth of approximately 9.1%. From 1911 to 1950, the Rio Grande thalweg gained 3,151 meters (10,338 feet) of length, a growth of approximately 6.3%. From 1950 to 1995/96, the thalweg gained 1,555 meters (5,102 feet) of length, a growth of approximately 3%.

The significant changes in wetted channel width discussed in the previous section might seem to disagree with the less significant percent change in the length of the thalweg. Also, examining the hydrograph (Figure 3) might lead to the expectation that there would be a greater difference between the thalweg measurements of 1950 and 1995/96, given the dramatic decrease in discharge. Several points address these apparent discrepancies. First, meander cutoff should be considered. The more a river meanders, the more meander cutoffs it creates. Thalweg length is subtracted when a meander is cut-off from the river. With time however, the river compensates for this loss in length by gaining it back by lateral erosion, which is its natural tendency.

The Rio Grande downstream of Brownsville has been a meandering river, with associated meander "cut-offs" long before human settlement/intervention, however, as discussed in Chapter 2, reductions in discharge trigger the response of increased meandering. This natural response has been counteracted, however, by human attempts to control a wandering international boundary. The installation of flood control systems including floodways, levees, dams and revetments, have all counteracted the river's tendency to meander. Still, the results of this study show an increase in thalweg length, and therefore meandering over time. In the early history of the LRGV, *bancos* and oxbow lakes were often created during flood events when physical laws dictated that water would be more efficiently conveyed in a more direct, rather than a meandering, path.

Comparison of the thalwegs for the three time periods of study was conducted (Figures 7, 8, 9). Evidence of a long history of meandering and meander cut-offs can be seen in all of the mosaics, but the degree of present-day meandering appears to have been stalled by hydrologic control measures. A dramatic difference between the habit, or pattern, of the 1911 thalweg and the 1950 and 1995/96 thalwegs is apparent. While the 1950 and 1995/96 thalwegs are fairly similar in their sinuous pattern (they appear to almost overlap at the scale of the mosaics), they contrast with the less sinuous habit of the river in 1911. When the 1911 topographic survey was made, the river was in a relatively natural state, under little human control. The time of the survey predates the construction of major dams and water control initiatives in the LRGV and in the entire Rio Grande basin, so it is a good baseline of comparison for change that occurred later. Between 1911 and 1950, there were at least four meander cutoffs, but there were no meander cutoffs between 1950 and 1995/96.

The lack of change between the 1950 and 1995/96 thalwegs despite the dramatic decrease in discharge, indicates that human hydrologic control measures have been moderately successful at keeping the river from forming new meander cutoffs. Land use in the floodplain is also indicative of human control of the river. Cultivated land and settlement can be seen in the 1950 and 1995/96 aerial photos inside river meanders indicating that these areas are not as susceptible to flooding as they once were. The anchoring of sandbars by vegetation also suggests that the Rio Grande below Brownsville rarely experiences major over-banks flows.

The anchoring and overgrowth of sandbars by vegetation can be seen in the mosaics of 1950 and 1995/96 aerial photographs (Figures 7 and 8). A close-up view is also provided (Figure 10). The clean, white sand in the 1950 aerial photographs indicates that the river was competent enough to keep its sediment load in motion. In contrast, the 1995/96 aerial photographs show that sandbars have become rooted by vegetation. Because the 1995/96 DOQQS have an infrared band of color, well-established vegetation is seen as red, and vegetation that is periodically mowed to maintain agricultural land and the floodway system, appears as reddish-brown.

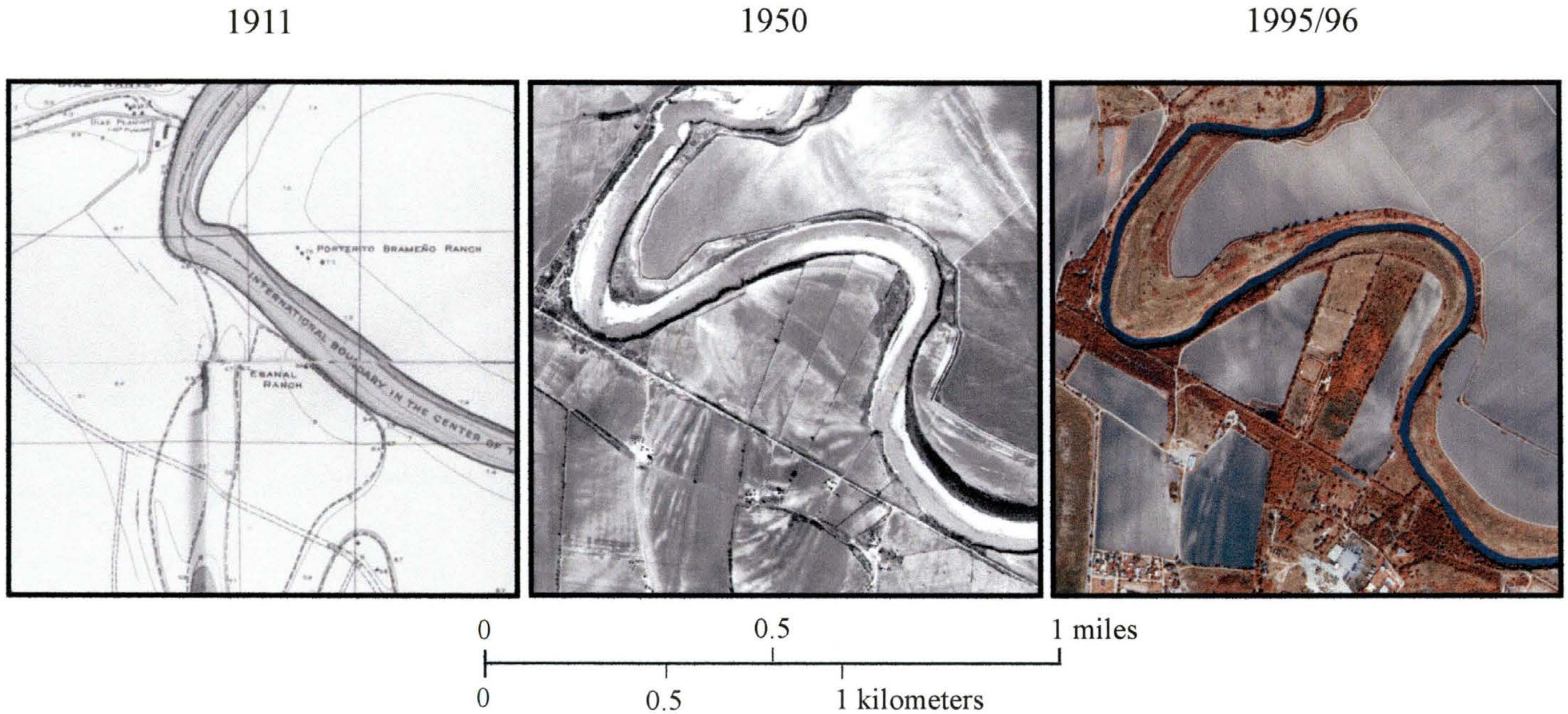

Fig. 10. 1911 Topographic Survey, 1950, and 1995/96 Aerial Photographs of the Rio Grande Below Brownsville, Texas, Showing Reduced Channel Width Over Time

The Rio Grande Out of Equilibrium

The reduction of discharge due to hydrological control initiatives has lead to a lack of over-bank flows and has decreased the river's competence to carry its sediment load. The lack of over-bank flows prevents the vertical accretion of floodplain deposits and without the natural process of the river periodically destroying and rebuilding its banks, sandbars become rooted with vegetation and the banks are "over-stabilized." Revetments further contribute to this unnatural galvanizing of the banks. As a consequence, the river deposits its sediment load within its banks and the result is aggradation. The channel narrowing and increased meandering documented in this study are evidence that aggradation is occurring.

The Rio Grande of the Lower Rio Grande Valley is a river that is attempting to adjust to dramatic changes in controlling variables, the most significant being discharge. Mueller (1975) found that the stretch of the Rio Grande between Rio Grande City and Laguna Madre, which includes the study area, is about twice as long as its valley length. In other words, the river is sinuous or meandering. Before human intervention, meander cutoffs were compensated for by lateral erosion. This is documented by the fact that from 1852 to 1898, approximately 60 meanders were cut-off, but the length of the river remained about the same (Mueller 1975). This demonstrates that the river system was in dynamic equilibrium during those years.

At the present time, human intervention is preventing meander cutoffs. The increase in the river's thalweg length (and overall length) suggests that the river is no longer in equilibrium. As the river becomes more tortuous, it loses energy. Less energy equates to less capacity to carry sediment load. The continuation of this trend, leads to the prediction that the narrowing and meandering documented in this study will continue in the future.

The historical Rio Grande that Mueller describes was one that can be classified as being in equilibrium with controlling variables and therefore can be classified as "stable" (Downs 1995). Downs' stable classification is used to describe a river whose deposition is balanced with erosion. The present day Rio Grande would be better classified as "depositional" because aggradation is occurring and the river is getting narrower (Downs 1995).

This might seem unexpected because even though there is a decrease in discharge caused by dams and water diversions, one might also conclude that there is a shortage of sediment since dams withhold much of a river's sediment supply in their tributaries. It should be realized, however, that immediately downstream of dams, the cold, sediment-starved water being released from the dam, scours the river's bed and scrapes up sediment. This extra sediment is deposited downstream of the dam (Collier, Webb and Schmidt 1996). Before the construction of dams and floodways on the Rio Grande, seasonal flooding would routinely remove the sediment deposited by tributaries. Now the dams and the floodway system attenuate most floods, sediment accumulates, and the river aggrades (Collier, Webb and Schmidt 1996).

CHAPTER 6

FUTURE RESEARCH AND CONCLUSIONS

The findings of this study raise many questions and point toward several avenues of future research. The suggested research projects discussed in this chapter would not only be meaningful independently; they would also benefit this thesis. This final chapter will address the potential further evaluation of meander evolution over time, the need for more in-depth analyses of discharge data and water budgeting, as lastly, the need for additional field and mapping data.

Further Analysis of River Meanders

To evaluate channel change over time caused by hydrologic control initiatives, this study focused on channel width and thalweg length. The same data generated by this thesis to evaluate channel change however, could be further mined to chart the evolution of meander patterns in light of progressively decreasing discharge and increasing human hydrologic control initiatives. A standard of what constitutes a meander wavelength, appropriate to the scale of the study reach, could be determined and applied consistently. The number of wavelengths and the radius of curvature of the wavelengths could then be determined for each period of study and compared. The relationship between radius of curvature and the number of meander cutoffs could also be evaluated.

Analyzing Discharge and Water Budgeting

Though out of the scope of this work, an in-depth statistical analysis of discharge would better gage the effect of hydrologic control measures on river morphology. Even though decreases in both the magnitude and variability of discharge over time can be gleaned from the hydrograph, statistical techniques could be used to quantify the discharge reductions. In addition, more directly linking changes in river morphology to changes in discharge, and measuring the time it takes the river to respond to changes in discharge, would be valuable. This would involve field investigations after major discharge events and a more thorough statistical evaluation of the discharge record.

Because it is the gaging station that is the most downstream, with the longest and most complete record, this study utilized discharge data from the Lower Brownsville gaging station. However, analyses of other gaging stations in the LRGV and in the upper part of the Rio Grande basin would benefit this study. Gaging stations on tributaries should also be evaluated to measure their contributions of recharge to the Rio Grande. In addition, there are gaging stations on irrigation canals and water diversion canals that could be used to estimate the amount of water withdrawn from the river. Knowing the inputs and outputs of the “river system” and using this information to generate a water budget would improve our understanding of the hydrology of the LRGV.

In Chapter 3 impoundment of major tributaries was discussed, as was the construction of diversion structures. Analyses of discharge data from tributaries and canals would allow for the estimation of historical versus current inputs and outputs. An obstacle to these analyses, however, is that gage data often do not extend far enough back in time to yield valuable information. Discharge data from gaging stations within the LRGV floodway system should also be evaluated. It would be extremely useful to quantify the distribution of water between the main channel and the floodway channels during major flood events.

The reduced capacity of the floodways is also an area ripe for research. An IBWC (1992) study revealed that the LRGV floodways are losing their capacity to convey floods like the main channel of the Rio Grande. The ability of the floodways to transport floodwaters relies on continued IBWC maintenance, including vegetation clearing. While the IBWC views the river and floodway channels as a flood conveyance system, conservationists see the river and surrounding riparian vegetation as a resource that should be unmanaged and left in a natural state for the preservation of habitat. The acquisition of land by groups such as the USFWS is working to keep the IBWC out of some areas, and threatening the integrity of the flood conveyance system as a whole.

Collection of Field Data

Though the methodology employed in this study evaluated aerial photos that were analyzed "in-house" using GIS software, field data would greatly enhance the results of this work. Calibrating the GIS measurements of channel width with field measurements of channel width would lend credibility to the GIS measurements. Field measurements of channel geometry would also add new dimension to this study.

The aerial photographs and maps used for this research are two-dimensional, so they cannot provide information about the depth or cross-sectional shape of the river. Field surveys however, would provide three-dimensional data. A recent IBWC (1992) study of the LRGV included cross-sections of the river, but there were not enough historical cross-sections measured at consistent locations, to confidently draw conclusions about trends in cross-sectional area and/or the depth of the Rio Grande within the study reach. Another valuable research pursuit would be to survey cross-sections of the river within the study reach at the same locations, over time.

The accumulation of sediment in the river and the river's capacity to transport sediment have both been shown to have a profound influence on river morphology, yet there has been little study focused on sediment budgets in the LRGV. The amount of sediment held within Falcon Reservoir should be determined, as should the amount of sediment scour taking place directly below the dam. The amount of entrained sediment in the river should be measured and the rate of erosion from the river's banks and bottom should be calculated. Furthermore, the amount of sediment contributed by erosion of the land surrounding the river should be measured. These data could then be used to calculate a sediment budget. Generating a sediment budget that accounts for inputs and outputs of sediment could be used to find ways to control sedimentation. Downstream of Elephant Butte Dam, for example, sediment retention dams have been built on arroyos that discharge into the Rio Grande during rain events. The dams have successfully reduced sedimentation (Day 1970).

The role of vegetation has also been established as an important control on river morphology in the study reach. Research throughout the Rio Grande basin suggests that non-native species such as tamarisk exert a negative effect on the river by over-stabilizing banks and encouraging sedimentation within the channel. Field investigation would help distinguish the different influences that native and non-native vegetation exert on river morphology.

Mapping and Spatial Analysis

The need for additional mapping is related to the need for more field data, but an important difference is that mapping generates spatial data. Once riparian vegetation (native and non-native) is identified in the field, it must be mapped so that it can be considered in relation to other physical characteristics of the river. The same is true for the mapping of revetments. The results of this study show that the Rio Grande is gaining length over time in the study reach. Mapping revetments would help determine if more length is being gained in areas that are being restored to a more natural state versus areas where revetments restrict the river's ability to erode its banks. Comparing the morphology of the areas of the river with revetments to areas without revetments will yield information about the amount of influence that revetments exert on river morphology.

Land use change should be mapped both in the field and in the office using historical maps. Changes in land use can then be correlated with changes in river morphology. For the same reason, the land purchased by the USFWS should be mapped. Mapping this land which is being restored to a more natural state, and observing the morphology of the river in these areas, might point to ways of better managing the river in the future. If the trend of narrowing documented in this thesis continues at its present extraordinary rate, the Rio Grande and the international boundary will be poorly defined downstream of Brownsville, Texas.

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