MORPHOLOGICAL CHANGES ASSOCIATED WITH GRAVEL MINING ALONG THE COLORADO RIVER, TEXAS

THESIS

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by

Cody Michelle Simmang, B.S.

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August 2007

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ABSTRACT

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SUPERVISING PROFESSOR: JOANNA CURRAN

There are countless bridges, buildings, parking lots, miles of highway, and numerous other structures throughout the United States. All of these structures require aggregate in their construction. Regions such as Austin, Texas, have expanded at an exceptionally rapid rate, and the demand for abundant sources of nearby gravels is being partially accommodated by floodplain mines along the Colorado River. While there is no doubt that gravel is necessary for the development, growth, and improvement of infrastructure, an assessment of how the excavation process and subsequent evolution of a mining site over time affects its surroundings, particularly the river system, should be addressed.

Many breaches into floodplain gravel mines are observed along the Colorado River. Streambed incision, bank erosion, channel widening, and channel straightening (through meander cutoffs) are documented results of gravel mining in fluvial environments. A concurrent loss of riparian vegetation is common, which can increase

runoff into the river. An increase in turbidity and change in average grain size can negatively affect aquatic life.

The natural rates of sediment transport through a river are influenced by many factors, including breaches in the bank between the channel and flooded gravel pit (leading to channel widening) and the increase in sand supply to the channel that occurs downstream of gravel pits. An analysis of the trends in sediment moving through areas affected by gravel mining provides data necessary to describe past morphological changes and help predict future changes associated with floodplain gravel mining. Three sites of past and present floodplain gravel mining on the Colorado River are studied, and the sediment transport rates through the river upstream and downstream of each site measured. A surface based transport model allows for the comparison of transport rates, particularly increased mobility associated with higher sand content downstream of the mines. Collection of material along gravel bars and on the channel bed was used to compare actual rates of sediment transport to calculated rates of movement. The model is used to predict rates of sediment transport over a range of possible flow events.

CHAPTER I

INTRODUCTION AND PURPOSE

Gravel mining is an important business in the United States as it supplies the material required to build the infrastructure of rapidly expanding cities. Gravel has several applications in construction, such as the production of concrete and road base, and must be produced at a rate to accommodate urban growth. Floodplain gravels are often exploited because they are easily accessible, abundant, require minimal processing, and are often located near areas of growth. The sand and gravel mining industry is not well regulated, and the problems stemming from these operations are usually poorly documented. Examination of how these operations affect the rivers they are so closely in contact with is important in assessing their impact on fluvial systems.

Gravel mining operations frequently locate pits very close to a main-stem river. When a site on the floodplain is mined too close to the river, the river can breach its banks and flow through the gravel pits. This typically happens to older pits that have been abandoned with no form of reclamation. These pits can be captured by gradual lateral migration or during large flood events. Upon capture, the problems of instream mining, such as incision of the stream bed, bank widening, changes in sediment size, loss of riparian vegetation, and degradation of aquatic life can occur (Sandecki 1989, Kondolf 1997, Mossa and Autin 1998, Saunders 2002). Stream capture of floodplain gravel mines has been documented in many areas throughout the United States, including along the

Colorado River in Texas (Saunders 2002). Several studies have acknowledged the effects of gravel mining on rivers in other areas, such as California and Washington. However, there are few publications available on the impacts of gravel mining in and near the major rivers of Texas. While studies of instream mining are extensive, floodplain mining, especially in cases where the river has changed its course to flow through abandoned gravel pits, is less well studied. There are several locations south of Austin where the river now flows through unreclaimed pits, and the old channel has been abandoned. The purpose of this research is to measure changes in sediment supply and transport as a result of gravel mining and to determine how river morphology is impacted by avulsions into mining sites along the Colorado River in Central Texas. This study will focuses on two instances where floodplain pits were captured by the main-stem river, as well as a floodplain pit that is in direct contact with the main channel only during high flows. Documentation of and comparison between each site will contribute to a better understanding of how floodplain mining processes affect river morphology.

CHAPTER II

STUDY AREA

The sites selected for this project are on the floodplain of the Colorado River southeast of Austin, between Del Valle and Bastrop (Figure 1). Specifically, these mines are along a 20 mile stretch of river between the Montopolis Bridge to just downstream of Webberville Park, in southeastern Travis County. This area is rapidly growing and contains many large gravel mining operations along both sides of the river. Additional growth and development is anticipated in the region stemming from construction of a new highway (state highway 130, expected to open by the end of 2007).

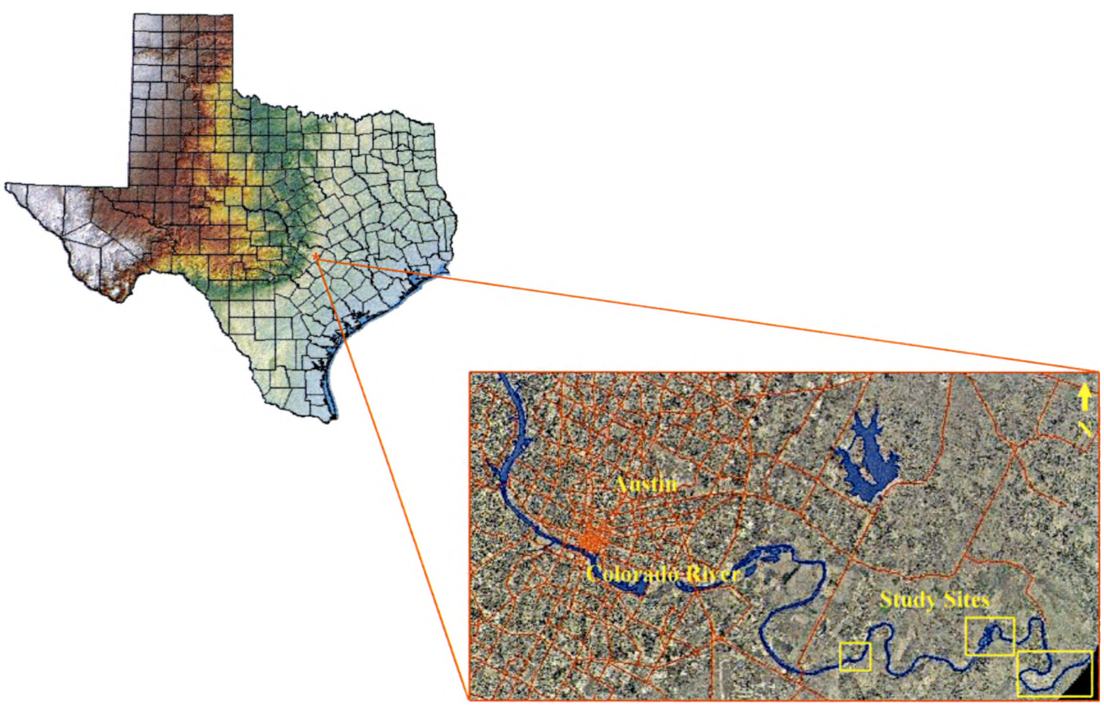

Figure 1: Map of study area. Research area is along the Colorado River in southeastern Travis County.

Gravel from these floodplain mines are currently being used for construction of the highway, and will likely be used to supply future development. Aerial photographs covering several decades show the evolution of each mining site. As these operations grow, they deplete entire meander bends along the river. The excavated pits fill with water since they are mined to a depth below the water table. As an operation expands, older pits are used as settling ponds to separate finer sediment from the washed gravels. During a flood, or by gradual lateral migration, the pits become part of the main channel. When this occurs, the old channel is often permanently abandoned in favor of a new channel course through the abandoned mine site. The specific pits that were studied are highlighted in yellow in Figure 2. There are three mining sites labeled 1-3, with each upstream site labeled A, and downstream labeled B, for a total of six study locations (1A, 1B, 2A, 2B, 3A, 3B).

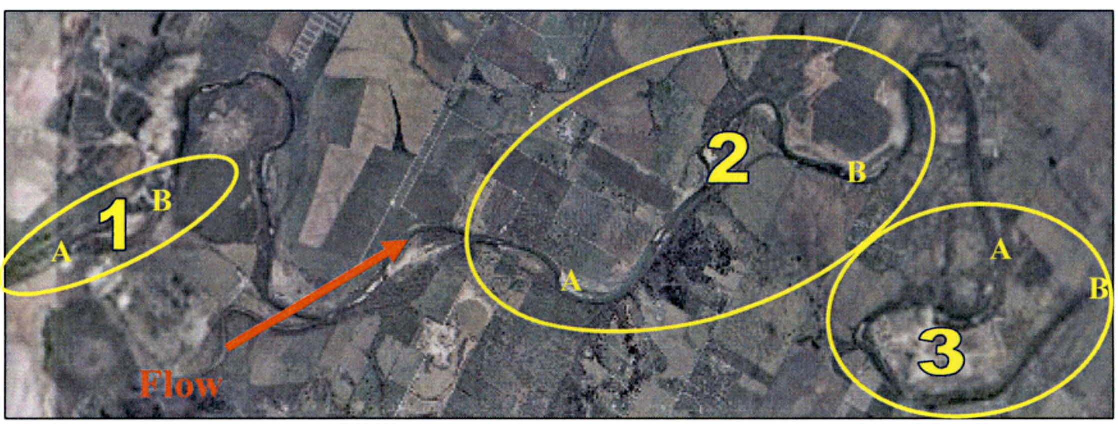

Figure 2: Location of the three gravel pits for study. Sites 1 and 2 are no longer active, but Site 3 is currently in operation. From Google Earth version 3.0.0762.0.

Site 1

Development of gravel pits at Site 1 is documented through topographic maps and aerial photographs. USGS 1:24,000 scale topographic maps were used for various years, as noted in upcoming figures. Aerial photographs were available through the City of

Austin website. Gravel pits are observed on the 1973 topographic map along the meander bend selected as Site 1. The pits and associated settling ponds expanded in size and proximity to the main channel throughout the 1980s, but remained isolated by a thin buffer of land and riparian vegetation. During a historic flood on Christmas Day, 1991, this buffer was breached and the river carved a new path through the former gravel pit (Saunders 2002). Flows associated with that flood reached 1076 cms at the Austin gauge (just upstream of Site 1A) and 1863 cms at the Bastrop gauge (downstream of all study sites), the largest on record since dam construction (Figure 3). Releases from upstream reservoirs caused high flows to continue for six months following the flood, as shown in the hydrograph from the Bastrop gauge (Figure 4). The new channel has become the dominant path for the river, with very little flow passing through the former channel. Figure 5 shows the evolution of the mine and course of the river from 1968 through 2003.

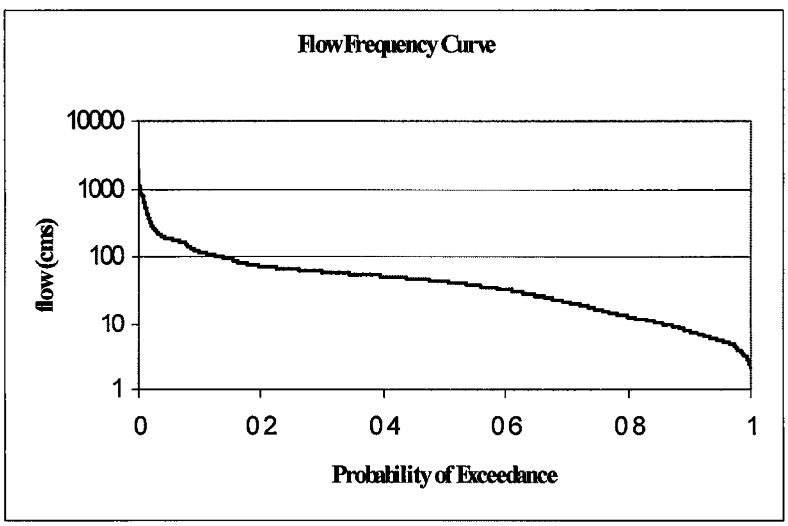

Figure 3: Flow frequency curve based on USGS data from the Bastrop gauge. Data ranges between 1960 and 2006, and shows the discharge associated with the 1991 flood to be the highest on record since dam construction.

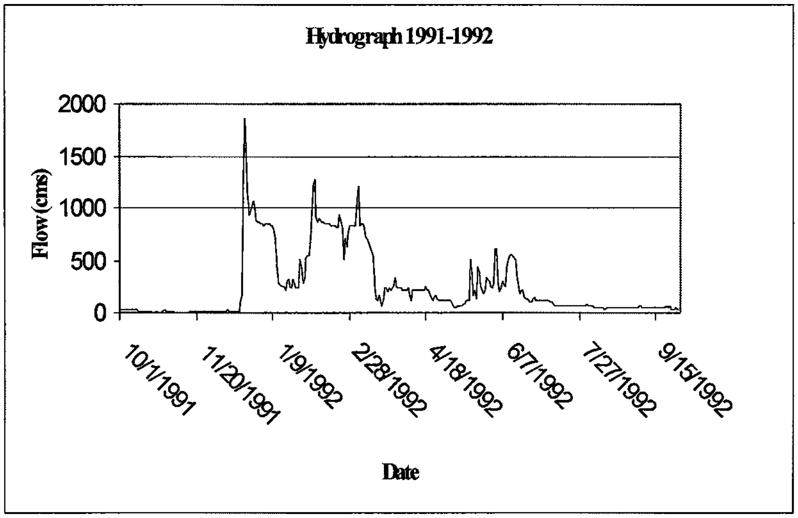

Figure 4: Hydrograph from USGS data at the Bastrop gauge. Flows associated with a major flood in late 1991 show discharge rates that exceeded 1800 cms and remained high for six months following from releases of upstream reservoirs. During this time the channel carved a new path.

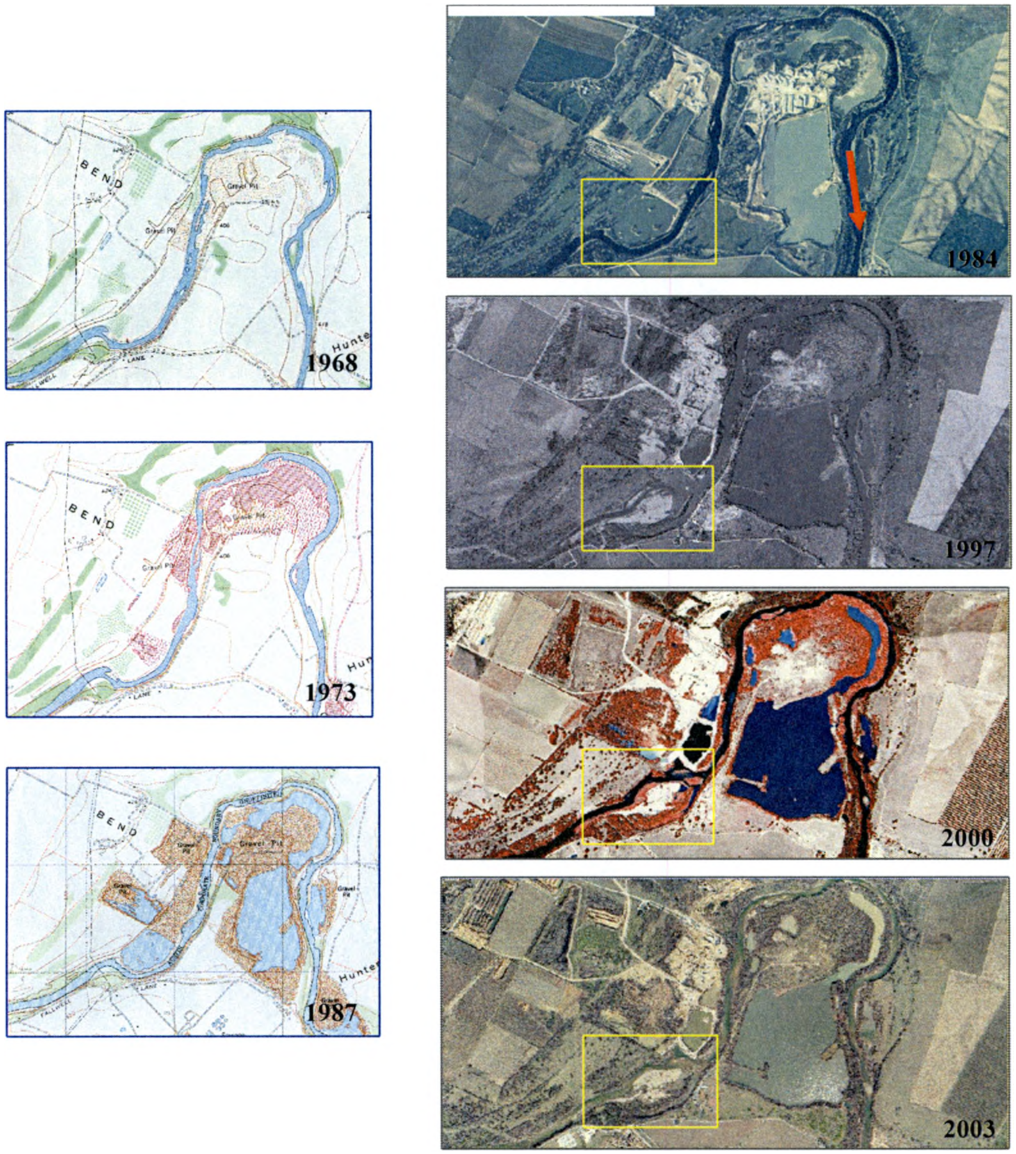

Figure 5: Topographic maps and aerial images of Site 1. These images show the evolution of the gravel pits and the course of the river from 1968 through 2003. During a flood on December 25, 1991, the river went overbank, flowed through an abandoned gravel pit, and reentered the main channel. This new channel became the preferred course of the river. Much of the former channel has since filled in. From USGS 1:24000 topographic maps and online aerial images from the City of Austin website http://coagis1.ci.austin.tx.us/website/COAViewer_dev/viewer.htm.

Site 2

The second site selected was being actively mined by 1973 along a small meander bend of the river. Aerial photographs show the river had avulsed into the pits by 1984.

Since then, the majority of the flow has traveled through the newer channel, and the old channel has narrowed dramatically. Figure 6 shows the evolution of this site over time.

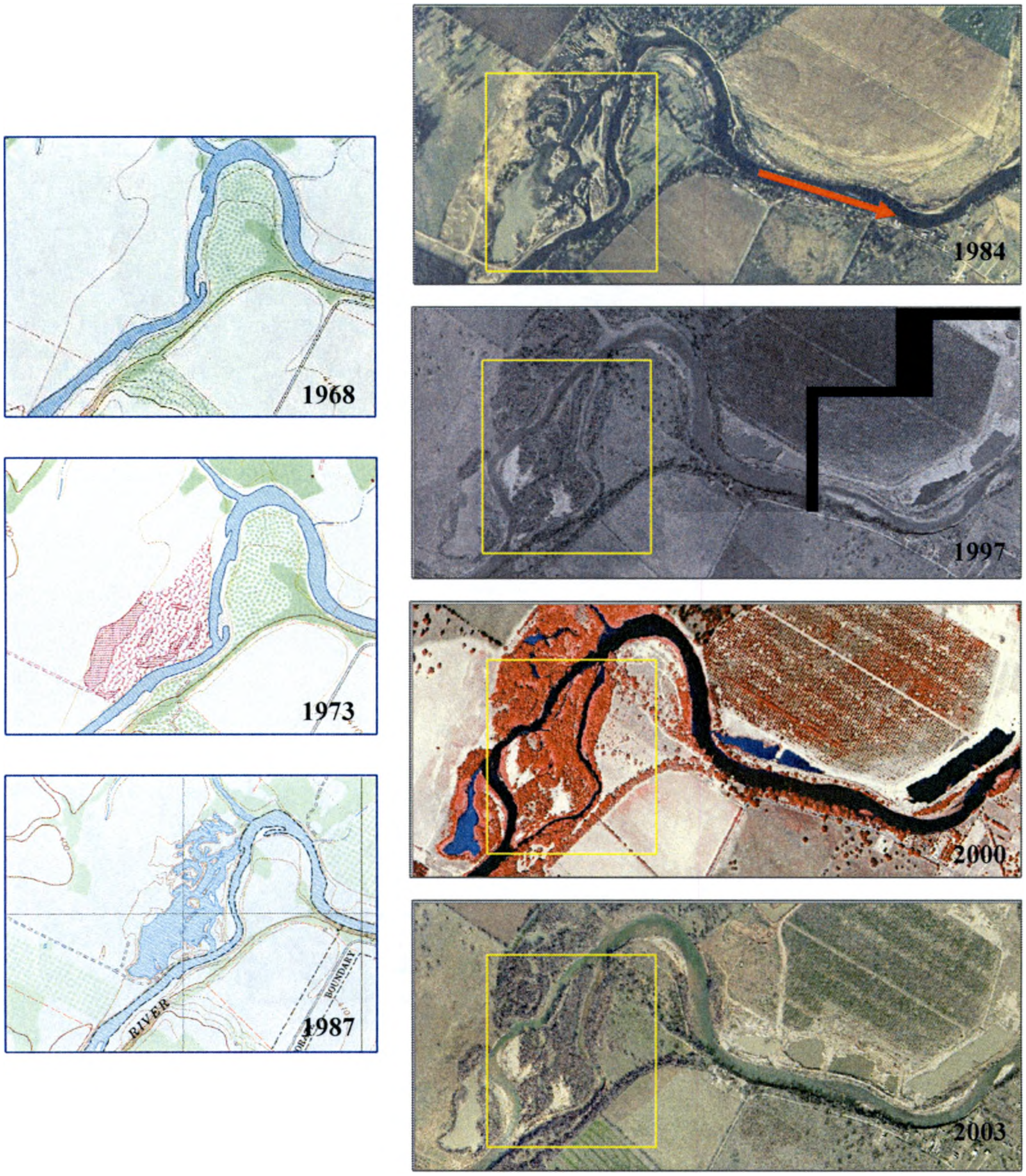

Figure 6: Topographic maps and aerial images of Site 2. These images show the evolution of gravel pits and the course of the river from 1968 through 2003. Some time between 1973 and 1984 the flooded pits were carved into a channel, which is wider than the original channel. Many of the banks along the new channel are poorly vegetated. From USGS 1:24000 topographic maps and online aerial images from the City of Austin website http://coagis1.ci.austin.tx.us/website/COAViewer_dev/viewer.htm.

Aerial photographs between 1973 and 1984 were not readily available to determine the exact time of the avulsion. However, hydrographs for this time period show several possible events that could have caused the breach (Figure 7).

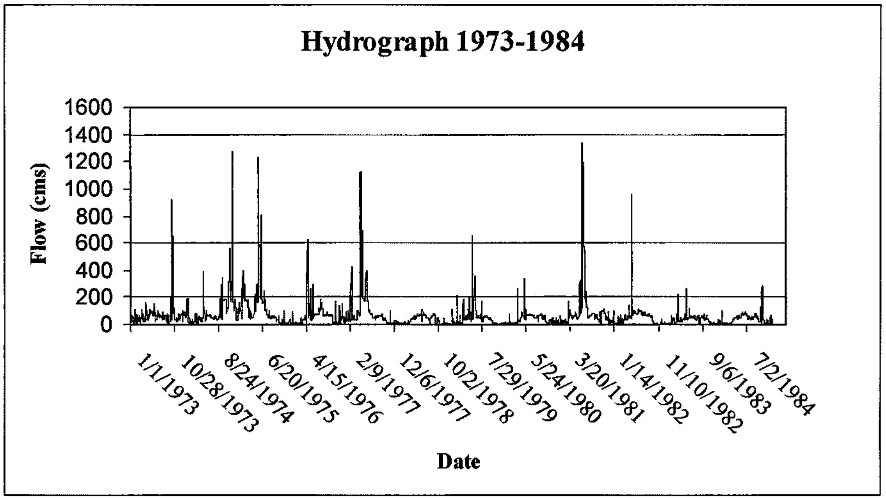

Figure 7: Hydrograph from 1973-1984. Several high flow events that likely caused the channel avulsion are observed in this hydrograph. Peak flow (based on USGS gauge data at Bastrop) during these years did not reach the levels that caused the 1991 avulsion, but were significant enough to have induced modifications to the river, either in one event, or over the course of several events.

Site 3

The third site selected is furthest downstream, very near the Travis-Colorado County line. This is an active mine along a large meander bend, and is typically separated from the main stem river by a levee, but can be inundated during high flow. Breaches between the mine and main channel have occurred during flooding, but an artificial berm is generally reconstructed after each event by the mining company. This mine has continued to expand since the mid 1980s. Figure 8 shows the evolution of this site.

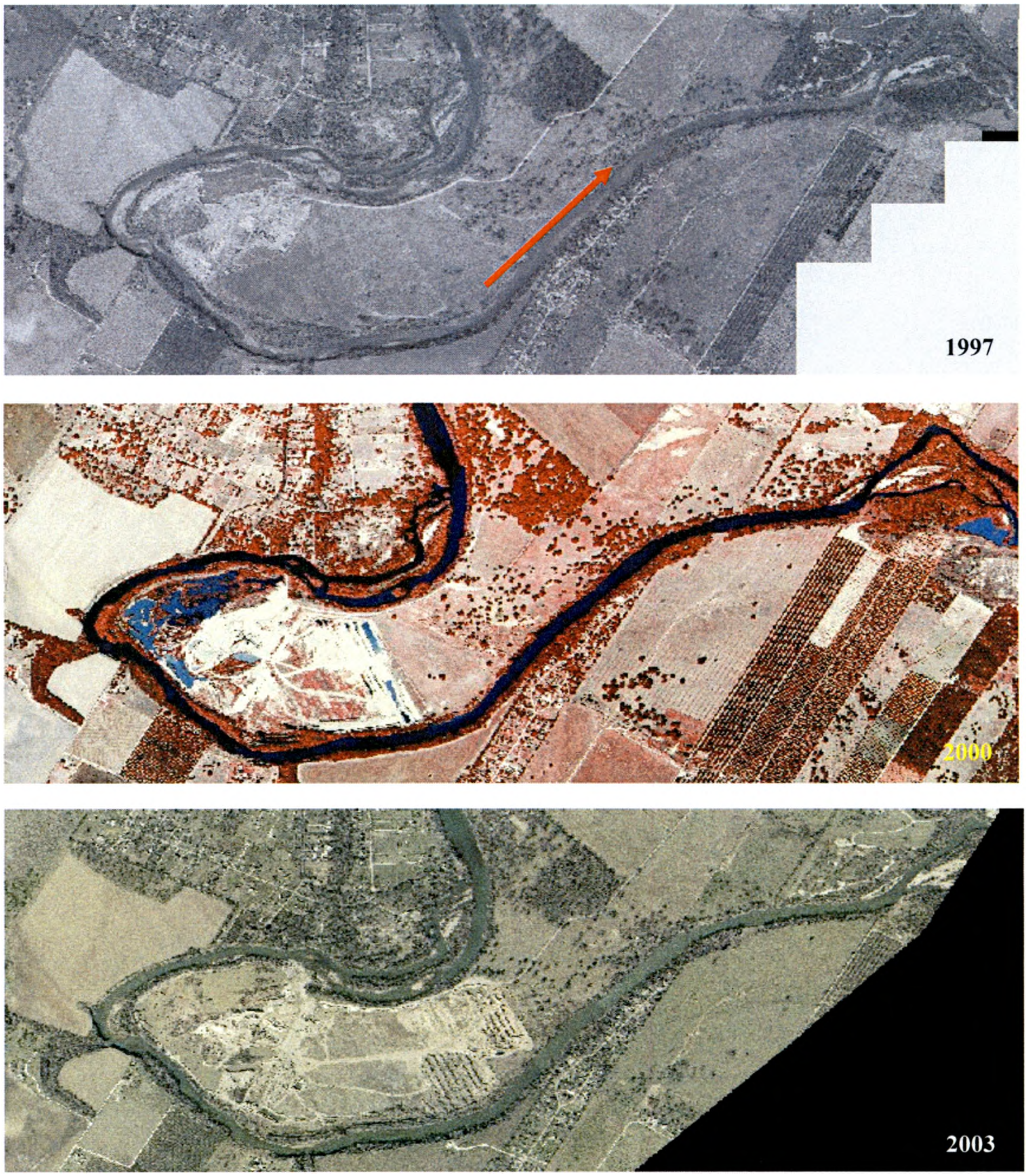

Figure 8: Aerial images from Site 3. These images show the growth of a gravel operation along a large meander bend in eastern Travis County. Images from the City of Austin Viewer http://coagis1.ci.austin.tx.us/website/COAViewer_dev/viewer.htm.

CHAPTER III

PHYSIOGRAPHY AND GEOLOGY

Climate

The Balcones Escarpment separates the semi-arid climate of the Edwards Plateau from the humid subtropical climate of the coastal plain. The study sites are located just east of the Balcones Escarpment. Cooler continental air masses that collide with moisture-saturated tropical air from the Gulf of Mexico result in large rainstorms over short periods of time in this region. These storms provide large quantities of runoff which transport coarse bedload material in the river systems draining the escarpment (Sears 1978). Average precipitation ranges from 76 to 86 cm per year, with peak rainfall typically in the spring and fall (Blum 1992).

The highly variable precipitation patterns in the Colorado River basin define its flow regime. Large amounts of precipitation fall on the area over short periods of time. Several features characteristic of this portion of Texas, including bedrock outcroppings, savanna-grassland vegetation, and the continued increase of impervious cover associated with urban growth all facilitate high rates and volumes of surface runoff. The rapid transport of runoff into the rivers results in the flashy flow regime characteristic of Texas river systems.

Depositional History

Floodplain and terrace deposits along the Colorado River reflect the late Pleistocene and Holocene alluvial history of Texas. Radiocarbon dating methods have aided in separating the depositional history into three major events (Blum 1992). In the late Pleistocene (20,000-14,000 yrs B.P.), continental glaciation created extensive paleoalluvial deposits in the upper portion of the basin (Blum and Valastro 1994). After glaciation and abandonment of the late Pleistocene floodplains, there was a period of major erosion and downcutting by the Colorado River and its tributaries (approximately 11,000 yrs B.P.). These processes left isolated deposits of paleoalluvium on top of bedrock in the Texas Hill Country. This period of incision established present valley depths (Blum 1992). East of the Balcones Escarpment, a decrease in slope produced slower stream velocities, increased meandering, and induced floodplain development.

A second major episode of sedimentation occurred during the very late Pleistocene to early to mid Holocene (13,000-5,000 yrs B.P. and 4,600-1,000 yrs B.P.), at which time most of the existing alluvium in the Colorado River valley was deposited (Blum 1992, Saunders 2002). A third episode occurred during recent time (1000 years ago to present) as modern floodplains with incised channels formed. The last two episodes of channel aggradation are separated by erosional disconformities and/or buried soil profiles (Blum 1992).

Deposition in the late Quaternary has been attributed to climatic changes, and increased flood stages (Blum 1992). The channel has adjusted from low sinuosity to high sinuosity, and has decreased meander wavelength and bankfull width (Baker and Penteado-Orellana 1977). As a response to the change in sediment supply and discharge, the channel of the Colorado River appears underfit when compared to the size of its floodplain. The large floodplains show the extensive depositional history of the river, but the modern river is much smaller and carries a smaller sediment load. In more recent times, changes to the river include the building of upstream reservoirs which regulate flow conditions. The main channel position is fixed within incised meanders, and overbank deposition is rare (Saunders 2002).

Stratigraphy

The oldest stratigraphic unit in the lower Colorado drainage basin is the Eagle Lake Alloformation, which overlies bedrock, and is comprised of late Pleistocene alluvium (deposited 20,000-14,000 yrs B.P). This unit corresponds to the extensive deposits associated with continental glaciation. An extended period of lateral migration, floodplain construction, and sediment storage was preserved during this time. The larger drainage system of that time period is evidenced by terrace deposits and underlying fill. This unit extends laterally below the surface onto the Outer Coastal Plain, where it is topped by younger formations. The Eagle Lake Alloformation is a coarse-grained gravely facies which is quarried for road base and building materials (Blum 1992). Deposits can be up to 8-10 meters thick.

The younger Columbus Bend Alloformation, which constitutes the main valley fill of the lower Colorado River, is inset against the Eagle Lake Alloformation (Figure 9). This formation is subdivided into three different members, the Columbus Bend Member 1 (deposited 13,000-5000 years BP, during the second major episode of deposition), the Columbus Bend Member 2 (deposited 5000-1000 years BP, during the third major episode of deposition), and the Columbus Bend Member 3 (the modern depositional system). Individual members define extended periods of time when sediment supply exceeded stream channel competence and capacity, and the fluvial system responded by adjusting channel and floodplain morphology, placing sediments into storage. Disconformities between allostratigraphic units represent time periods when sediment supply was limited relative to transport capacity (Blum 1992). Figure 10 illustrates the evolution of late Pleistocene and Holocene alluvial fill.

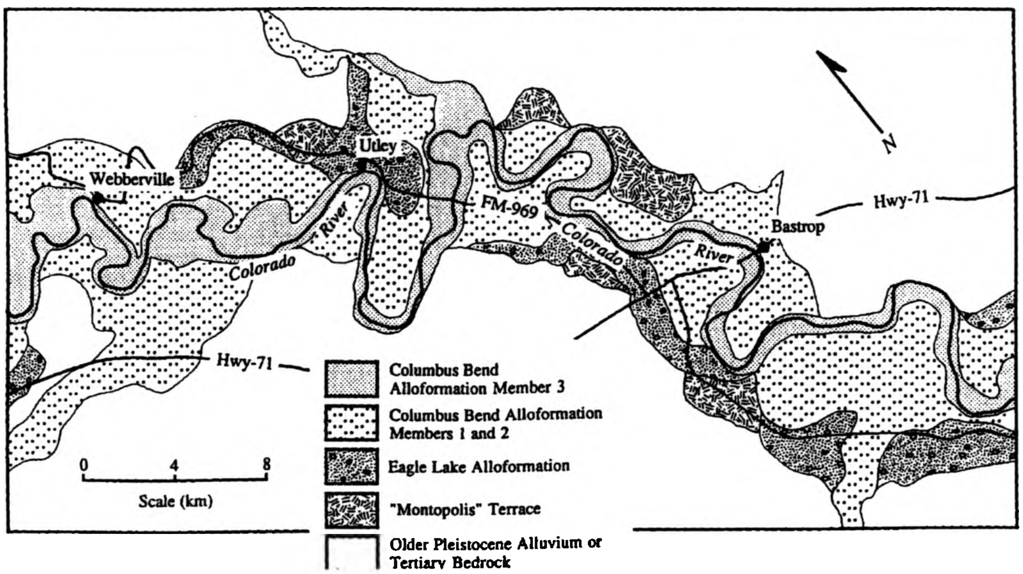

Figure 9: Geomorphic map of the lower Colorado Valley between Webberville and Bastrop. This map illustrates surface distribution of allostratigraphic units (from Blum 1992).

Lithology

Upland sources of sediment are important components of downstream deposition (prior to dam construction), since 92% of the Colorado River drainage basin is upstream of the Balcones Escarpment (Figure 11), including all major tributaries. East of the Balcones Escarpment, the drainage basin of the Colorado River narrows considerably, and has no major tributaries (Blum 1992). Without new inputs of sediment from large tributaries, it is reasonable to assume that most of the sediments in the lower Colorado

River basin are derived from sources upstream of the Balcones Escarpment. The study area is in the central portion of the river system, where sediment is transported from upstream and deposited in the Gulf Coast Basin. The sediment source has been cut off by the building of a series of six dams along the river, which were constructed between 1937 and 1960.

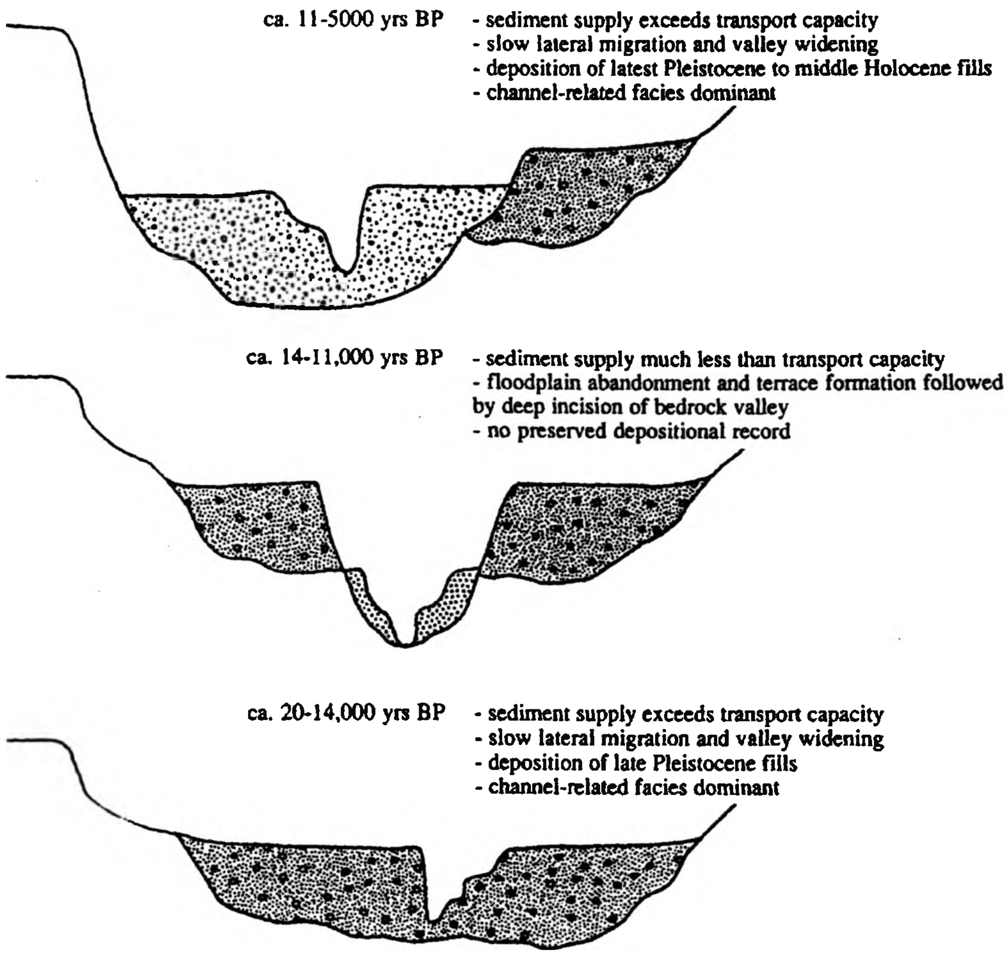

Figure 10: Schematic of valley cross sections. The depositional history of late Pleistocene and Holocene alluvial terrace and valley fill is summarized in these cross sections (from Blum 1992).

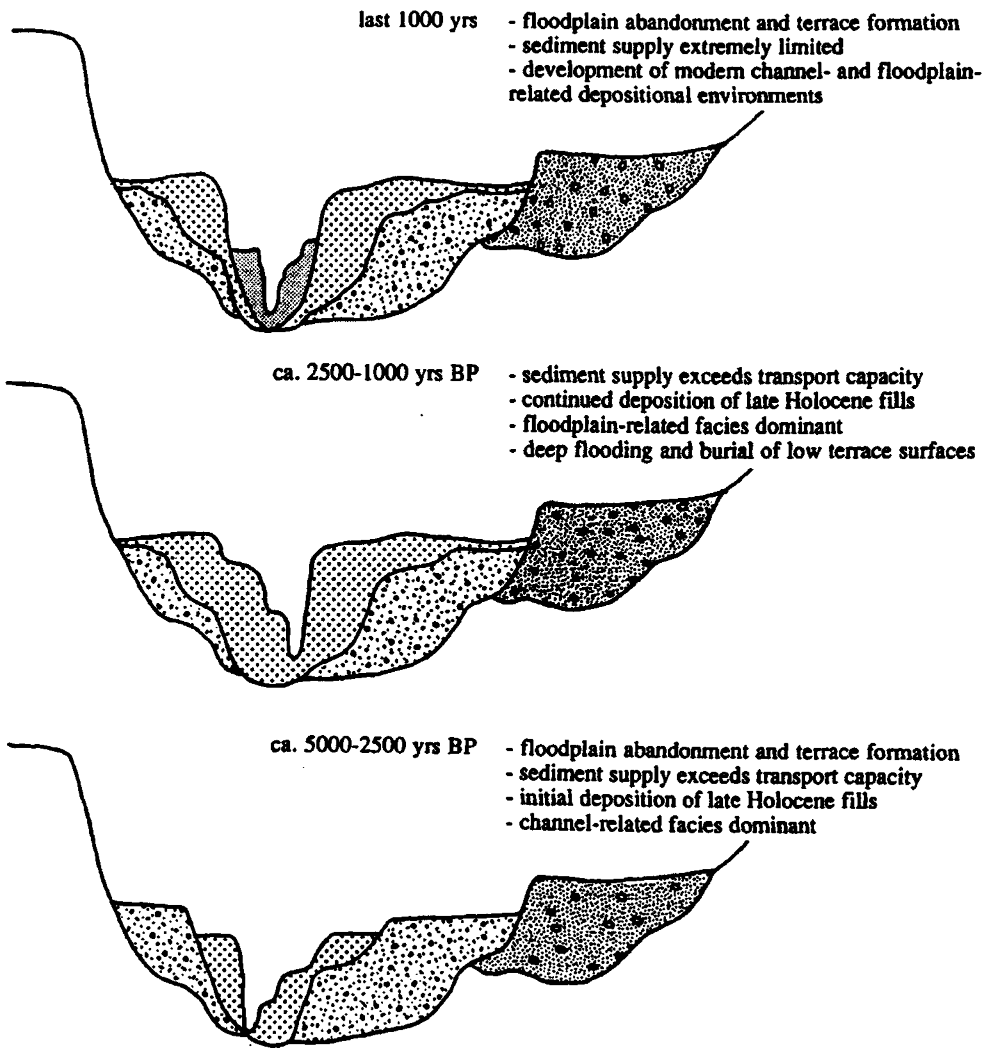

Figure 10 (continued): Schematic of valley cross sections. The depositional history of late Pleistocene and Holocene alluvial terrace and valley fill is summarized in these cross sections (from Blum 1992).

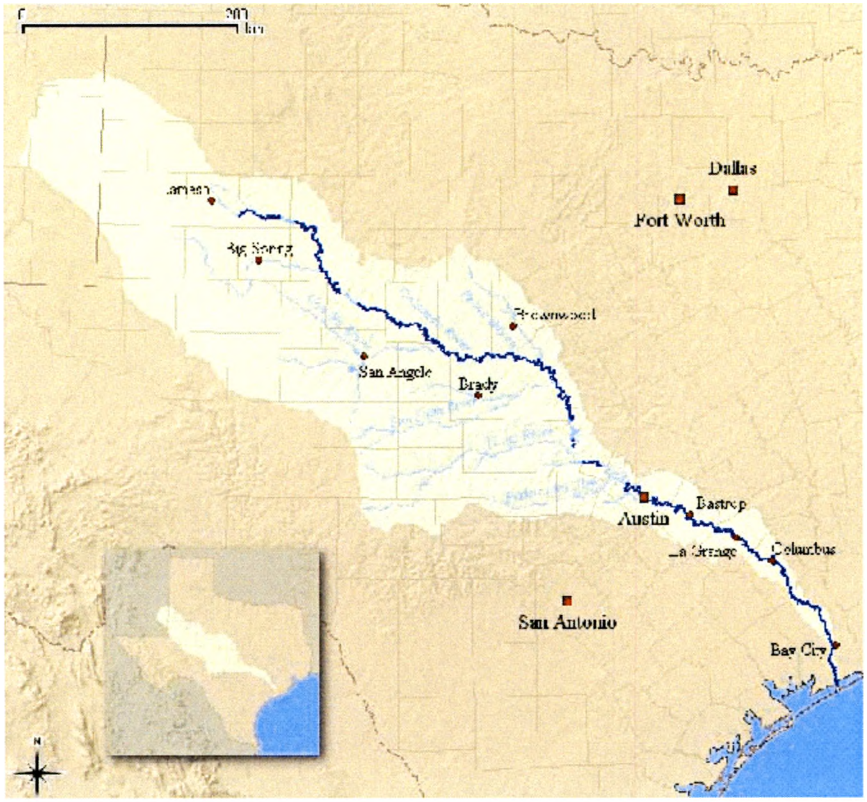

Figure 11: Outline of the entire Colorado River drainage basin.
From: http://en.wikipedia.org/wiki/Image:ColoradoTexas_Watershed.png

The diverse geology of the upper Colorado drainage basin is reflected in the heterogeneous rock types found in bedload sediments stored in floodplain and terrace deposits. Gravels are dominated by quartzite derived from the Neogene Ogallala Formation at the Southern High Plains margin, chert from the Cretaceous Edwards Limestone and Edwards Plateau portion of the drainage system, and quartz grains and granite clasts from the Precambrian rocks from the Llano Basin (Sneed and Folk 1958, Bradley 1970, Baker and Penteado-Orellana 1978, Blum 1992). Limestone rock fragments from the Edwards Plateau are prevalent in the upper drainage and in the region near the Balcones Escarpment, but are only a small percentage of the gravels in the sediment load further downstream. Locally-derived sandstone clasts are also observed in the gravel-sized fraction of river sediments throughout the lower Colorado River valley, but tend to break into their individual components as transported further downstream. Bioturbated clay clasts (Figure 12) are observed and included in pebble counts. These clasts are an important component of material captured by the nets. This material likely comes from nearby sources along the banks of the river, since the material is easily broken apart during transport and crumbles when dried.

The study of fluvial sediments gives valuable information concerning stream channel and floodplain response to change. The provenance of sediment gives indication of the amount contributed by various sources, as well as distance transported over time.

Mineral assemblage is also an important consideration in transport calculations, because the specific gravity of the sediment is a component of both shear stress and transport rate. Calculations in this study used a value of 2.65 (specific gravity of quartz), because quartz is the dominant component of the majority of the rock types. It is recognized that calcite (s.g. 2.71) and various feldspars (s.g. 2.55-2.76) are important components of the sediment transported. Having a quasi-equivalent proportion of sediments with specific gravities greater and less than that of quartz, this 'average' value is considered representative.

Figure 12: Erosion of bank material. Bank erosion is the source of large bioturbated clay clasts found in the bedload and on gravel bars (left). These clasts easily break apart when dried and smaller fragments are transported downstream (right). Photo by author.

River Morphology

The longtime assumption in geomorphology, based on studies in the humid temperate environments of the northeastern United States, associates channel forming discharges with a recurrence interval of 1-3 years (Wolman and Miller 1960). More recent studies have found channel forming discharges to vary dramatically depending on several factors, including climatic and physiographic conditions. Baker and Penteado-Orellana (1977) found channel forming floods to be much larger and less frequent than the 1-3 year interval, particularly in arid environments with flashy flow regimes. He argued that strong resistance to erosion in predominantly bedrock channels, and the high threshold shear stress required to transport gravel-size sediment loads common in streams of Texas result in channels that are morphologically adjusted to high magnitude but low frequency flood events (Blum 1992). Such events shaped the channel of the Colorado River but have recently been reduced in size and frequency due to dam construction.

The previously referred to series of dams, constructed from the 1930s to 1960, provide flood control, hydroelectric power, and recreation. The Lower Colorado River

Authority regulates discharge from these dams, thereby controlling downstream flow. State-approved instream flow requirements have been set to provide water for a "healthy" river habitat, as well as flow into Matagorda Bay. Minimum discharges vary by season, depending on needs (i.e. hydroelectric power, irrigation by farmers) as well as by year (depending on lake levels, precipitation upstream).

Flooding still occurs when lake capacity is exceeded or when there is significant rainfall downstream of the dams. USGS gauging stations have sufficient data prior to damming (as early as 1898) to distinguish the natural flow regime in the hydrograph. An order of magnitude drop in maximum peak discharge coincides with the time of dam construction (Figure 13).

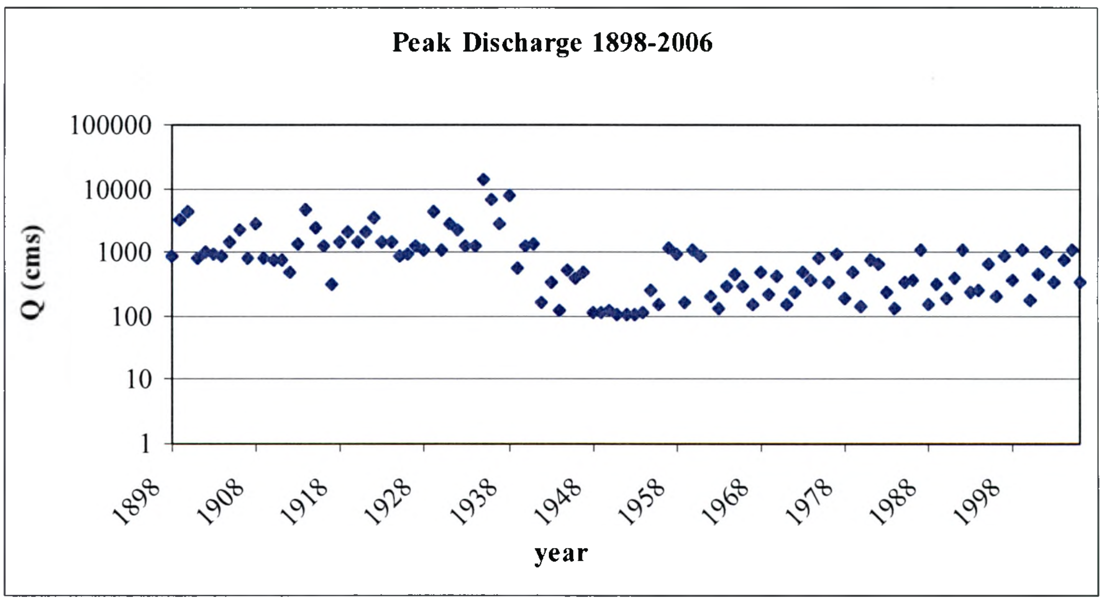

Figure 13: Peak annual discharge from 1898-2006. Note the dramatic drop in discharge in the late 1930s (data from USGS gauge at Austin).

Work by Blum (1992) explores discharge characteristics of the Colorado River from records prior to impoundment, and are confirmed and updated by this study. Hydrologic data for the Austin gauge from 1898-1937 shows maximum peak discharge to be 13,620 cms, with a stage of 15.3 meters. Mean annual flood and stage for the time period is 2147 cms and 9-10 meters, respectively (stage values from Blum, 1992). Mean annual discharge is 77 cms with an estimated stage of 1.59 meters. By contrast, the same parameters from 1960 to 2006 for the Austin gauge are significantly lower (Table 1). Maximum peak discharge for this time period is 1116 cms, with a stage of 7.4 meters. Mean annual flood and stage are 476 cms and 4.43 meters. Mean annual discharge is 44 cms, with a stage of 1.26 meters. There is a gradual increasing trend in maximum peak discharge in the years after dam construction, presumably from changes in land use and continued development. Figure 14 shows the recurrence interval for different flows pre- and post- dam construction. The recurrence interval for the mean annual flood is just under 3 years for both time frames. However, the magnitude of such an event is dramatically lower post-dam construction (2147 cms compared to 476 cms). The mean annual flood prior to dam construction is almost two times the magnitude of the maximum annual flood value after dam construction.

Table 1: Magnitude and stage of peak and average flows prior to and following dam construction.

	pre-dam (1898-1937)		post-dam (1960-2006)	
	Q (cms)	h (m)	Q (cms)	h (m)
Maximum Peak Discharge	13620	15.3	1116	7.4
Mean Annual Flood	2147	9 to 10	476	4.43
Mean Annual Flow	77	1.59	44	1.26

* based on USGS gauge data at Austin

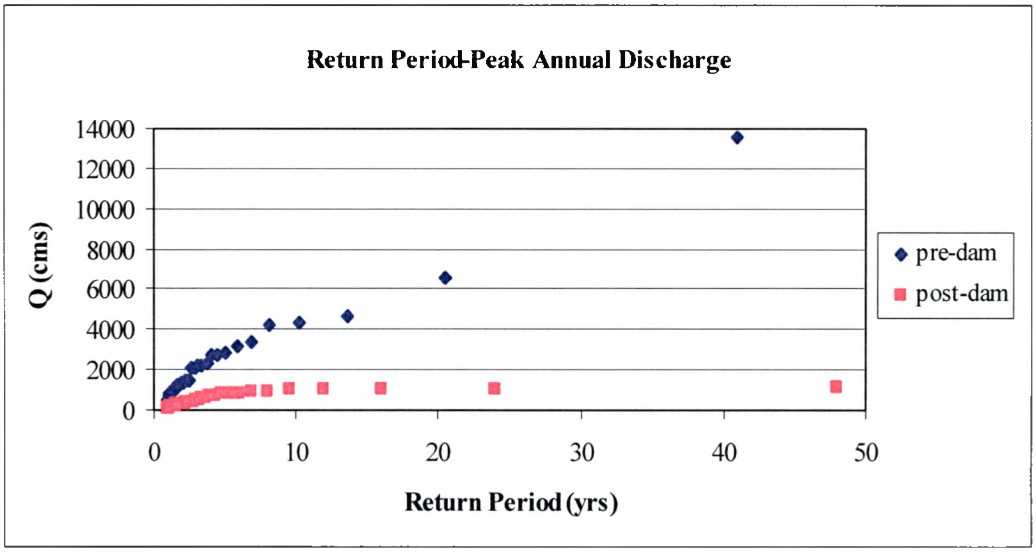

Figure 14: Return period and corresponding magnitude of flows. A comparison of annual discharge prior to dam construction (1898-1937) and following dam construction (1960-2006), based on USGS gauge data at Austin.

CHAPTER IV

BACKGROUND

Source of Gravel

River sediments are desirable for use in highway construction because the material in the bed is a naturally graded, sorted, and rounded product (Sandecki 1989). Weak materials and fine sediments are typically washed downstream leaving behind a high quality deposit that requires less processing than gravel from other sources. These sites are typically close to transportation routes, thereby reducing transportation costs (Kondolf 1994a). Length of transport is an important consideration when choosing a mining site because gravel is a high volume, low cost commodity. Gravel from nearby river sources is commonly used in many products, including those that do not require material at the high-grade level of river gravel (Kondolf 1994a). Crushed stone is a viable alternative to many projects requiring aggregate, yet fluvial gravel sources are often used because of their abundance, ease in processing, and location (Roell 1999).

Mining Methods

Various methods used to extract sand and gravel in and around river systems. Some have fewer environmental consequences than others, but all affect the surrounding area. The most common methods include in-channel pit mining, bar skimming, floodplain pit mining, and terrace pit mining (Figure 15).

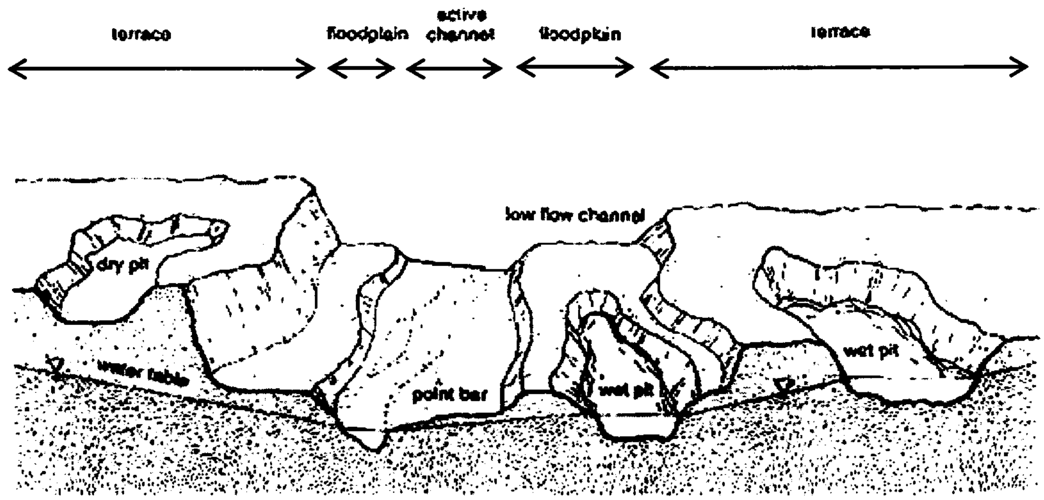

Figure 15: Schematic of various mining methods. Notice the proximity to the active channel and the water table. From Kondolf (1994a).

Aggregate is excavated from the active channel bed below the thalweg during in-channel pit mining (Kondolf 1994a). This mining method changes channel geometry and bed elevation. While in-channel mining can have benefits, such as local flood protection, the process changes the dynamic equilibrium of a river system, modifying prior river stability (Sandecki 1989). The river will work to re-establish equilibrium, resulting in erosion of the bed and banks.

Using the bar skimming method, in-channel gravel bars are removed above the low flow channel elevation (Sandecki 1989). The shape of the streambed is modified to a wide, flat cross section where baseflow creates a thin sheet of water across the channel width. Mining in the active channel (in-channel pits or bar skimming) not only changes the shape of the channel, but also affects aquatic life, by selective extraction of material and increased turbidity in the water (Kondolf 1994a).

Mining aggregate in floodplain pits is considered a less damaging method for obtaining gravel (Sandecki 1989, Roell 1999). Floodplain mining is away from the active channel bed, and generally separated from the river by a small levee or buffer zone. This type of mining can be wet or dry, depending on the elevation of the surface relative to the baseflow water elevation of the channel (Kondolf 1994a).

Terrace mining is similar to floodplain mining. Pits are excavated, and can be wet or dry (depending on the depth compared to the water table). Since terrace mining is away from the active floodplain, this method is considered to have the least impact on the fluvial system.

Problems with Mining in the Floodplain

While a direct connection between environmental problems and instream pit mining and bar skimming has been established, the problems resulting from mining in the floodplain are not as immediate. Many of the negative impacts to the river system from floodplain mining occur when the main-stem river breaches the buffer zone between it and the gravel pits. When this occurs, the problems with instream mining, such as incision, channel widening, change in sediment size, loss of riparian vegetation, and loss of habitat, are now problems surrounding the (former) floodplain pits.

Floodplain mines become part of the active channel when the river migrates laterally and erodes the banks separating the two bodies of water. When considering an area over decades, such an event is likely to occur unless upstream reservoirs can control very large floods (Kondolf 1994a). Even though upstream reservoirs along the Colorado River have reduced the magnitude and frequency of such floods, flows high enough to break buffer zones have occurred since impoundment. The path of the river is typically made shorter and straighter through the pits, since they are mined on the point bars of large meander bends.

Examples of captured floodplain mines by the active channel are documented for the Colorado River in Texas (Saunders 2002), the Amite in Louisiana (Mossa and Autin 1998), the Yakima River in Washington (Kondolf 1997), and the Little Piney River in Missouri (Roell 1999). In 1971, two pits on the Yakima River were captured when the river breached levees and began to flow through gravel pits. Ironically, the incision attributed to gravel mining at the site began undercutting the highway for which the pits had originally been excavated (Kondolf 1997). The Little Piney River in Missouri has also experienced capture of floodplain pits. Here the stream temperature rose 17° C following capture of mining pits and subsequent input of water and sediment to the main channel (Roell 1999).

Channel incision is a major problem caused by both instream gravel mining and captured floodplain pits. A loss of extracted sediment from the channel disrupts the balance between sediment supply and transport capacity. The stream responds by incising, both upstream and downstream, from the point of excavation (Kondolf 1997). Excavated pits have a locally steeper gradient, and as the river moves through the site, a knickpoint erodes upstream (Figure 16). Knickpoint migration, or headcutting, can continue for kilometers upstream of the excavation site. The incision can develop into a local concern when it undermines bridge supports or exposes pipelines and other structures buried within riverbeds (Collins and Dunne 1990). In California, a highway bridge over Stony Creek exhibited scour related to nearby gravel mining (Kondolf and Swanson 1993). Along the Drome River in France, gravel mining has caused incision that undermined bridges and other infrastructure (Kondolf et al. 2002).

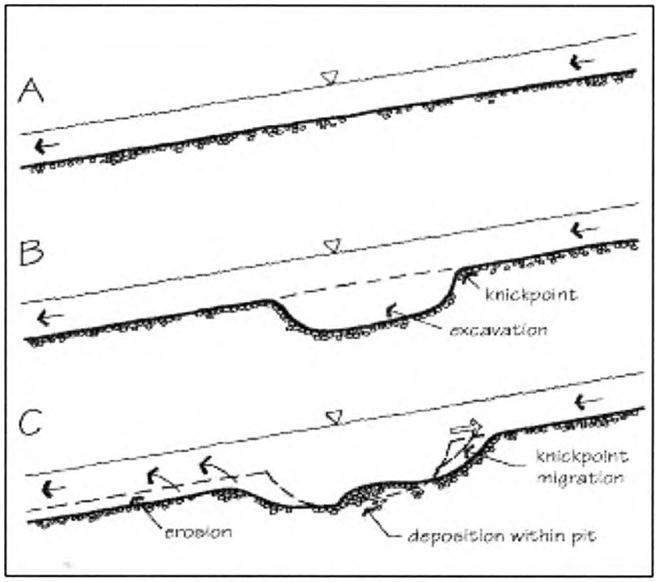

Figure 16: Knickpoint migration.

A. Profile of stream prior to mining.

B. Excavation of bed material (analogous to gravel pit or pond prior to avulsion).

C. During high flows or after an avulsion, a knickpoint moves upstream as erosion occurs along the area of locally increased slope. This sediment is deposited in the pit while erosion occurs on the downstream end of the pit as the river tries to re-establish equilibrium (a relatively smooth channel bed). (modified from Kondolf and Swanson, 1993).

A knickpoint was discovered during a trip on the Colorado River in April of 2007, downstream of Site 1B (Figure 17). Here, waters from a very large lake formed by extensive gravel excavation have cut through to the main channel (Figure 18). Another knickpoint was found in June of 2007 between Sites 3A and 3B, where a breach into and out of a mining pond had formed after a large flood (Figure 19). This breach was repaired by the mining company so that boaters could not have access to the pond, but water continues to flow between the pond and main channel.

Figure 17: Approximate location of breach downstream of Site 1. The red arrow shows the location of the breach between a large pond and the main channel. From Google Earth version 3.0.0762.0.

Figure 18: A knickpoint downstream of Site 1. This knickpoint formed when a breach occurred between a large pond from a former gravel pit and the main channel. Photo by author.

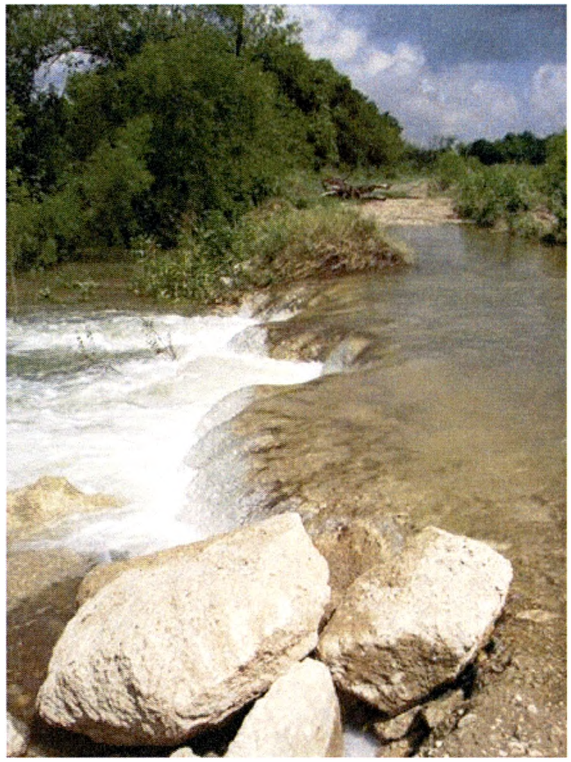

Figure 19: A knickpoint between Site 3A and Site 3B. This knickpoint was formed when the buffer between a large pond and the main channel was breached during a flood. Photo by Kevin Anderson.

An increase in erosion of the bed and banks, causing channel migration in formerly stable reaches, are all results of incision (Kondolf 1994a). Lateral instability occurs from increased stream bank erosion and channel widening. Incision increases stream bank height, which leads to bank failure when the bank collapses under its own weight. Subsequent channel widening results in a shallowing of the streambed and can produce braided flow or subsurface intergravel flow (Roell 1999, Ojos Negros Research Group 2004).

Because the thickness of alluvium over bedrock differs along the Colorado River compared to other places of study, an evaluation of river response to mining activity in this environment is necessary to assess predicted differences. For example, in California and Washington (where extensive studies have been conducted) the climate is generally cooler and wetter than in Central Texas. By contrast, Central Texas is a semi-arid environment with mixed bedrock-alluvial rivers. This difference will likely yield a varied response by the Colorado River. While rivers such as the Yakima in Washington and the Upper Sacramento in California have thick alluvial beds to incise into, the Colorado has a much thinner layer of alluvium overlying bedrock. Therefore, the Colorado may be more likely to experience channel widening from sediment-starved waters at some locations downstream of gravel mines rather than incision. When looking at the cumulative problems of several mines within a reach of river, channel widening may also lead to an increased capture rate of downstream pits.

Changes in sediment supply and mean grain size of the bed material are documented results of gravel mining. Coarsening of river material occurs locally as a result of selective extraction of finer sediment combined with removal by channel incision. The loss of finer material can result in the formation of a lag deposit of cobbles and boulders on the stream bed (Kondolf 1994a). A well documented case of bed coarsening occurred along the Upper Sacramento River, where a combination of upstream dam construction and gravel mining caused an increase in local sediment size (Kondolf 1994a).

In other environments, removal of gravel-sized sediments reduces the average size of bed material. For example, along the Lower Mississippi River, river bends and banks are stabilized by revetments or dikes. This man-made control restricts lateral migration and prevents the river from cutting into new sources of coarser sediment. In this environment, gravel dredged from the river is not replaced by upstream sources, which leads to a depletion of coarse materials in the area (Legasse et al. 1980).

After an avulsion, when the river flows through the bare soils left in abandoned gravel mines, it picks up loose sediments and transports them downstream, resulting in an increased supply of finer sediments. This has been observed along the Colorado River, particularly after a flood, when finer sediments are deposited over coarser gravel bars downstream of mines.

Riparian vegetation provides bank stability and prevents runoff. A loss of riparian habitat is common in and near gravel mining sites. The direct removal of vegetation by heavy machinery occurs when constructing the mine pits in the floodplain. Further destruction of local vegetation occurs when it is buried by stockpiles of gravel (Collins and Dunne 1990, Kondolf 1997, Saunders 2002).

A loss of habitat and spawning gravel is associated with gravel mining. In situations where local coarsening occurs, fish are unable to move the larger sediment to build a nest. This happened on the Upper Sacramento River, where the effects of instream gravel mining were compounded by the construction of a dam. The California Fish and Game Department of Water Resources artificially replenished the spawning gravel in the area at a cost of over $22 million (Kondolf 1994a). Much of this gravel is subject to scour and loss during high flow, making reclamation of the site difficult. Benthic invertebrates are negatively affected by the increase in turbidity of the water (Kondolf 1994a). An increase in suspended sediments blocks light necessary for many aquatic species. Fine sediments can also block interstitial spaces necessary for fish to lay their eggs (Schmitten 1996).

Local groups have brought attention to the possible threat to water supply and quality. The pits excavated in the floodplain are in close hydrologic continuity with the river, and track fluvial water level. The water table is very shallow in this region and there is some concern about contaminating and/or depleting the water supply when pits are dug to a level deeper than the water table (Village of Webberville 2005).

Problems with Regulation of the Industry

Many of the problems with reclaiming abandoned gravel pits stem from the lack of regulation of the industry. The Rivers and Harbors Act of 1899 and the Clean Water Act of 1972 help to regulate the building of structures and the discharge of pollutants into the nation's rivers. Each state can set guidelines for the aggregate industry that go beyond the scope of these acts, but most of the regulation focuses on instream mining. While permits are necessary for a gravel operation, they tend to be poorly enforced and do not set up strict guidelines for mining in the floodplain (Kondolf 1994b).

In Texas, agencies including Texas Commission on Environmental Quality (TCEQ), Texas Parks and Wildlife Department (TPWD), and Texas Department of Transportation (TXDOT) have a part in the regulation of the gravel industry. Since a variety of problems stem from mining sites, different aspects (physical, biological, social) are of concern to different agencies. TCEQ regulates surface water discharge and point source air discharge. TXDOT regulates the safety aspects of sand and gravel pits, but mining and reclamation of these pits are not regulated under state law (Aggregate Research Industries 2005). As with many agencies, there is a lack of technical expertise and resources to properly set up and enforce regulations set on the gravel industry.

Permitting

Permits are generally easy to obtain, and are often given out by people who are not sufficiently trained in geomorphology or hydrogeology to recognize the vulnerability of an area to extensive excavation (Kondolf 1994b). Gravel miners frequently operate without permits, or violate the parameters of their permits, such as exceeding the maximum excavation amounts. TCEQ established the Clear Streams Initiative in 2004 to assess the impacts of gravel mining after complaints of major environmental degradation on the Brazos River associated with a mining operation in very close proximity to the river (Figure 20). The report stated that 46% of gravel mines statewide were operating without a permit (Shankle 2004). It is difficult to assess the cumulative effects of mining on a particular reach of river, partially because of this lack of regulation.

Figure 20: Aerial view of an operation along the Brazos River. This mine was later closed, but brought attention to the problems associated with gravel mining. From Brazos River Conservation Coalition website: http://www.brazosriverconservationcoalition.org.

After the publicity on the Brazos River, State Bill 1354 was drafted to protect water quality along the Brazos from the negative impacts of gravel mining. The bill formed a pilot permitting program set to run from 2005 through 2025. The program requires an individual discharge permit from existing quarries in the 100-year floodplain or within one mile of a navigable water body in the watershed. New quarries are prohibited within 1500 feet of the water. This bill applies to only 115 miles of the Brazos River below Possum Kingdom in Palo Pinto County to the Parker-Hood County line. These regulations are considered too stringent for the mining industry to follow and are only being applied to one reach of the Brazos River for a trial period of twenty years. After the program is completed, the success will be evaluated, but not until then will it be considered for other rivers in Texas (Kathryn Nichols-Texas Parks and Wildlife, personal communication).

Guidelines for Gravel Mining Operations

While lack of regulation is a major concern, study of areas currently mined or likely to be mined in the future is necessary to know how much gravel can be extracted without major environmental degradation. Several factors must be incorporated to establish a sediment budget for a particular area. Maximum extraction with minimum impact is dependent on how much sediment is replenished in a given amount of time. For regions such as the Colorado River, where sediment replenishment won't occur (mined sediments are from a much higher flow regime and prior to damming), reclamation plans or (at a minimum) prevention from avulsions should be established. The cumulative effects of multiple mines in an area must also be evaluated to determine how mining changes the entire river system and not just a single reach (Kondolf 1994b).

Aside from the lack of thorough documentation of pit operations on Texas rivers, a broad gap in the literature lies in the analysis of stream features prior to excavation, documentation of the amount of aggregate removed, and analysis of stream features after excavation. While this information is imperative for instream mining, it is also necessary for floodplain pit mines, especially when attempting to establish a reasonable buffer zone between the excavation site and the river in an effort to prevent capture of pits by the river. Such an analysis will help form a model to predict effects of extraction on other locations in the future (Storm 1982).

CHAPTER V

METHODS

Several methods originally developed to document morphological change from instream mining sites can be applied to this study, where the barrier between the river and floodplain pits has been breached and pools from the mines are now part of the main channel. These methods will be used to determine the factors that affect sediment supply to the Colorado River, how the river transports sediment (what is available to transport, and what is actually moving for a certain flow), and how erosion and deposition of sediment affect the morphology of the channel.

A combination of methods have been shown to be effective and are well described in studies by Collins and Dunne (1990), Kondolf and Swanson (1993), Florsheim et al. (1998), Kondolf et al. (2002), and Saunders (2002). These methods include a survey of the longitudinal profile of the river, analysis of sequential topographic maps and aerial photographs, channel cross sections, sediment samples of bed and bank material, stream gauge data, historic sediment yield, changes in land use, and a review of extraction permits. Of these methods, this study will rely on topographic maps and aerial photographs, channel cross sections and flow measurements, stream gauge data, and sediment samples of bed material and gravel bars. Observations of land use change over time will be evaluated in a qualitative manner. The data collected were analyzed using the surface based transport model of Wilcock and Crowe (2003) to determine transport rates necessary to move different size sediment in the channel and will be compared to what is actually moving under a certain flow.

Reviewing topographic maps and repeat aerial photographs from various years allowed for the determination of where (and approximately when) several avulsions had occurred, as well as potential sites of future avulsions. USGS 1:24000 topographic maps from 1968, 1973, and 1987 were used, as well as aerial photographs from 1984, 1997, 2000, 2003, and 2004. The aerial photographs are available online through the City of Austin website. Changes in the landscape before, during, and after various mining operations were established are observed between images (Figures 5, 6, 8). By cross referencing the year of the image with stream gauge data, the specific flood event could be found (or narrowed to a few events) that resulted in the avulsion. The images give an idea of the character of each site, such as gravel pit size, shape, and proximity to the main channel as well as the amount of vegetative cover. A comparison of these data among sites was helpful in determining locations prone to future avulsions. The 2004 infrared images (Figure 21) were exceptionally useful in showing mines that were flooded during a high flow event. One limitation to aerial images was the lack of very recent photographs. There are several new or expanded mines seen from the river that are not on the available images.

Figure 21: Image of the gravel mine at Site 3 inundated during a flood in late November 2004. Flows reached 1068 cms at the Austin gauge (upstream of site) and 1537 cms at the Bastrop gauge (downstream of site). From USDA National Agriculture Imagery Program 2004.

Aerial photographs were useful in determining reaches suitable as field sites to measure sediment upstream and downstream of each gravel mine. Each location was selected along riffles shallow enough to wade across. Sites were selected far enough away from current mining activity to minimize influences of active mines, such as the influx of fines from runoff over barren ground and excessive sedimentation in channels (Figure 22).

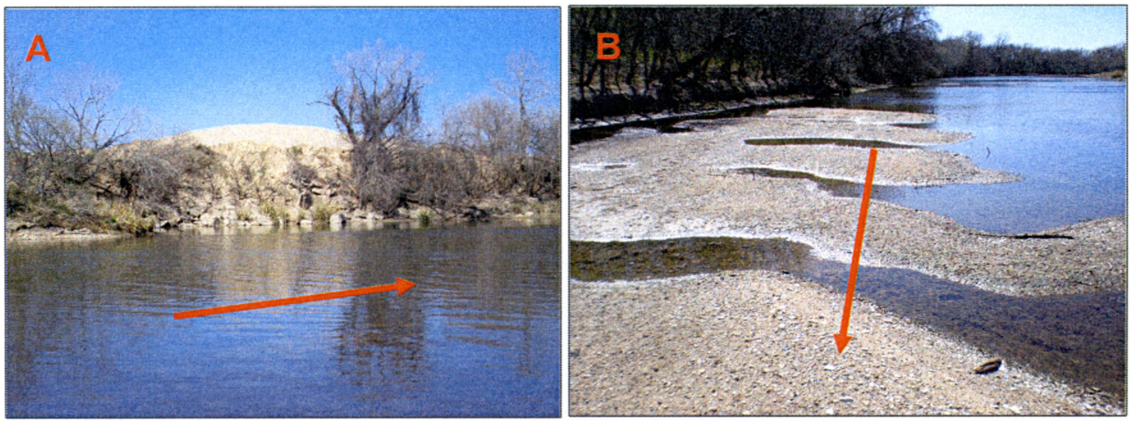

Figure 22: Increase in fine sediment from active gravel pits. A. Material introduced into the channel from an active pit just below Site 1B. Measurements were taken upstream of this location to minimize the influence of this pit. **B.** A dramatic increase in sand is noted in the channel downstream of A, because of the loose sediment available for transport into the channel, and the lack of riparian vegetation. Photos by author.

Cross sections of the river illustrate channel bed bathymetry. Flow was measured at each cross section using a Marsh McBirney Flo-mate 2000 at 20 and 80 percent total depth at set increments across the channel. Discharge measurements are important to associate flow to each size fraction of sediment transported. Measurements at each site were compared to nearby gauges, to relate amount of flow between each study site to the regularly measured gauges. A relationship between discharge at each site to those measured at the gauges allows for better prediction of what the flow conditions are at each site when individual field measurements are not feasible (i.e. floods). Stream gauge data is also used to determine the discharges associated with past buffer zone breaches. This information can be used in the future to help determine the size of buffer zone necessary to prevent pit capture.

A detailed description of methods used to sample sediment in wadable gravel and cobble bed streams is available in Bunte and Abt (2001). Sampling of bed material is performed to obtain the particle size distribution of the riverbed and channel bars. With the size and distribution of bed material, bedload transport rates, transport capacity, and flow competence can be calculated to help predict the behavior of the river and better understand processes shaping the morphology of the river. These methods were translated to the Colorado River, a gravel bed river with some regions dominated by bedrock and depths frequently exceeding wadability (several meters deep).

The monitoring of sediment through the use of portable bedload traps (Figure 23) allowed for a between site comparison of bedload mobilized by a certain magnitude of flow. Sediment traps were set above and below two breached sites and one active site that is inundated at high flows. Collected sediment at these locations illustrates what is being transported under certain flow conditions. Differences in measured transport were compared upstream and downstream of each site, as well as between sites.

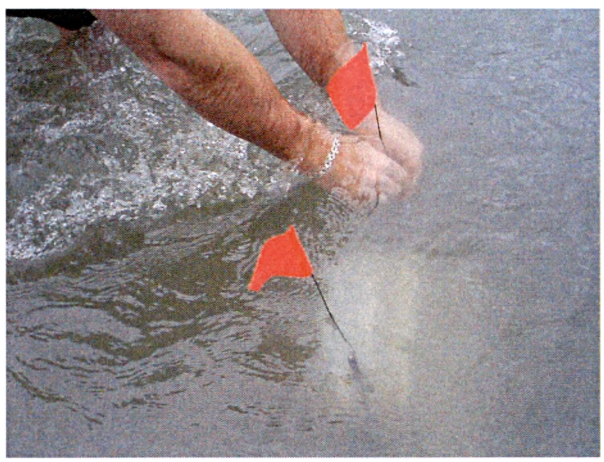

Figure 23: Portable bedload traps. These traps were flagged and placed in the channel for this study. Photo by author.

For a complete assessment of the spatial variability in transport rates, multiple bedload samplers would ideally be set across the channel at equal increments of approximately 15% of the channel width (Ryan and Troendle 1997). However, the time and resources required (numerous sediment traps) made the method impractical for this particular study. Further, flow velocities in the thalweg were typically too strong (greater than 1.5 m/s) to wade into and set out nets. Bunte and Abt (2001) describe both safety hazards and likelihood of inaccurate sampling results associated with flow velocities greater than 1.5 m/s. The 0.6 m rebar that came with the traps was replaced by 1.2 m rebar to ensure the traps stayed in place.

One sediment net was set out at each site for approximately 24 hours. The nets were set in the thalweg of the channel, or as close to it as possible when high velocities prevented such placement. The distance each net was from the bank, time, depth, and velocity were all noted. While this method does not account for what is moving at all locations along the cross section, it does provide data for what is moving at a certain velocity associated with that location in the cross section, and can be compared to what is expected to move under such conditions.

Surface material along gravel bars was sampled using the pebble count technique described by Wolman (1954). A minimum of 100 pebbles were counted along gravel bars upstream and downstream of each site. This sampling technique has recognized shortcomings, such as operator bias toward larger particles as described in Bunte and Abt (2001), but efforts were made to minimize this source of error. Grain sizes included in the count are very fine gravel (2.8 mm) to large cobble (256 mm). Counts were conducted along gravel bars that are inundated at bankfull or higher flows but exposed during low flow. These counts allow for a comparison of the size distribution of what moves (or is available to move under high flow conditions) upstream and downstream of a mine, as well as between sites. Because gravel bars represent deposits of sediment mobilized by the river, the grain size distribution determined by pebble counts along the bars was assumed to be comparable to the distribution along the bed at each site. This grain size distribution was also used to calculate theoretical transport rates of each size fraction and compared to actual transport rates of grains captured in the nets. Grains from the pebble counts were separated into 1/2 ϕ grain size bins for analysis.

A visual estimate of percent sand (<2 mm) on the surface was made for each location both on the gravel bars and in the channel. An increase in sand content on the surface of the gravel bars was noticeable following increased flows. Percent sand used in these analyses is estimated for times of relative stability (i.e. not after a major flood).

Data collected became input for the surface based transport model of Wilcock and Crowe (2003). This model calculates the flow necessary to transport each size fraction of sediment and total sediment transport rates associated with a particular discharge. Unlike other sediment transport models, such as Ashida and Michiue (1972), Parker (1990), and Powell et al. (2001), which exclude the fraction of sand from the model, the model of Wilcock and Crowe incorporates the influence of sand on transport capacity. The following are the governing equations in the model. Development and further description of the relationships of these equations are given in Wilcock and Crowe (2003).

$$q = Uh \quad \text{(Conservation of mass)}$$

where q=water discharge per unit width (m^2/s), h=flow depth (m), U=mean velocity (m/s)

$$\tau = \rho g h S \quad \text{(Conservation of momentum)}$$

where τ = shear stress (kg m/s^2), ρ = water density (kg/m^3), g = acceleration of gravity (m/s^2), S=bed slope

$$\frac{U}{U_*} = 8.1\left(\frac{h}{2D_{50}}\right)^{1/6} \quad \text{(Flow Resistance)}$$

where U_* = shear velocity ($U_* = \sqrt{ghS}$, m/s). The above equation is the Manning-Strickler form of the Keulegan resistance relation used in open channel flow. An equivalent roughness factor (Nikuradse's roughness, k_s) of two times the average grain size ($2D_{50}$, in meters) is used in this equation.

$$\tau^*_{r50} = 0.021 + 0.015\exp[-20F_s]$$

where τ^*_{r50} = the dimensionless reference shear stress for grain D_{50}, and F_s = fraction of sand on bed surface. The reference shear stress is the minimum shear force necessary to mobilize a measurable quantity of a specific grain size.

$$\tau^*_{r50} = \frac{\tau_{r50}}{(s-1)\rho g D_{50}}$$

τ_{r50} = the reference shear stress for grain D_{50}, and s = the ratio of the specific gravity of sediment to the specific gravity of water ($s = \rho_s/\rho$).

$$\frac{\tau_{ri}}{\tau_{r50}} = \left(\frac{D_i}{D_{50}}\right)^b$$

where τ_{ri} = the dimensionless reference shear stress for grain *i*, D_i = surface grain size *i*.

$$b = \frac{0.67}{1 + \exp\left(1.5 - \frac{D_i}{D_{50}}\right)}$$

where b is a hiding function. This function decreases transport rates for finer fractions by increasing the reference shear stress for size fraction *i* and increases transport rates for coarser fractions by decreasing the reference shear stress for size fraction *i* relative to the overall reference shear stress. Hiding is important to consider in the mixed-size sediment of a natural river because smaller grains are sheltered from the full force of flow by larger grains. Therefore, these smaller grains are often not mobilized until the larger grains are transported and they become exposed.

$$W_i^* = \begin{cases} 0.002\phi^{7.5} & \text{for } \phi < 1.35 \\ 14\left(1 - \dfrac{0.894}{\phi^{0.5}}\right)^{4.5} & \text{for } \phi \geq 1.35 \end{cases}$$

where W_i^* = the dimensionless transport parameter, and $\phi = \tau/\tau_{ri}$

$$q_{bi} = \frac{W_i^* F_i U_*^3}{(s-1)g}$$

where q_{bi} = the transport rate of grain size i (m^2/s).

CHAPTER VI

RESULTS

Site 1A *[30°12'44.22" N, 97°37'03.76" W; WGS84 Datum]*

Aerial photographs in Figure 24 show the upstream and downstream locations where cross sections were taken (yellow line) and pebble counts conducted (red X). Site 1A is at a riffle of an armored gravel bed channel following a relatively straight reach of river that is not impacted by nearby gravel mining. A bridge is being constructed several hundred meters upstream of this location. The rip-rap used to stabilize the bridge is noted as it may influence fluvial processes at this site.

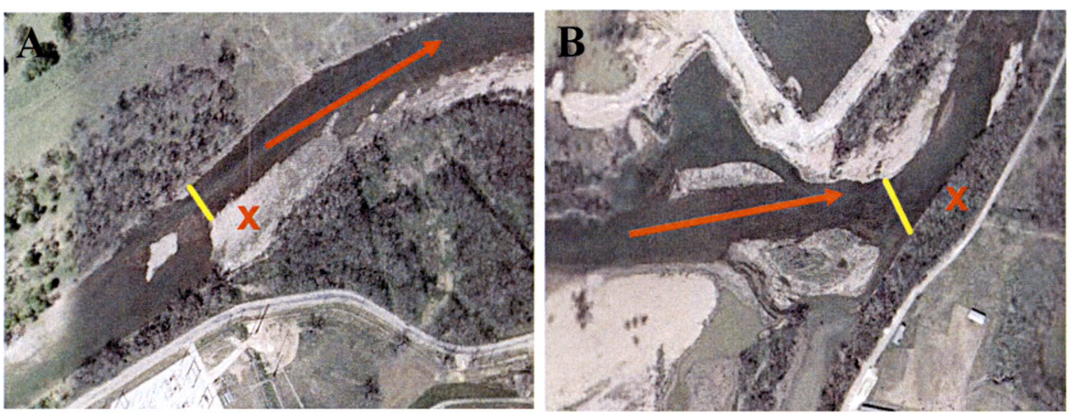

Figure 24: Location of cross section measurements and pebble counts for Site 1A (A) and Site 1B (B). From Google Earth version 3.0.0762.0.

Two cross sections were measured to show channel bathymetry and discharge. Flow measurements were compared to the Austin gauge, upstream of this site, and were found to be an average of 3% greater than the discharge at Austin (with a range of <1% to

6% over). Walnut Creek discharges into the Colorado River between the Austin gauge and Site 1A, possibly accounting for the increase in flow at this location.

Parameters measured in the field, such as width, depth, velocity, discharge, average grain size, and percent sand, as well as calculated values for the same parameters at bankfull are summarized in Table 2. The channel is 23 meters wide and 0.74 meters deep at its thalweg. Average velocity is 0.56 m/s, and 1.29 m/s in the thalweg. Bankfull width and depth are estimated to be 91 meters and 14 meters, respectively. Average grain size of the bar adjacent to the riffle is 32mm (Figure 25). Percent sand on the bed surface is estimated to be 10%. Average diameter of grains caught in the portable bedload trap is 5mm.

The amount of sediment transported at various rates of flow (and associated depths) for each size fraction, based on pebble count data, is modeled and the results shown in Figure 26. The most mobile size fraction for this site is 16 mm, and the least mobile is 128 mm. The transport rates for individual size fractions of sediment at Site 1A were modeled for depths of 1 m to 5 m over the gravel bar, and ranged from 0.0007 kg/hr to 1192 kg/hr (Table 3). Discharge rates range from 134 cms for a depth of 1 m to 742 cms for a depth of 5 m. The return periods associated with these rates are approximately 29 days and 1.46 years, repsectively (Table 4).

Table 2: Measured and computed values.

	1A	1B	2A	2B	3A	3B
Measured Values						
width (m)	23.01	37.49	48.77	52.12	54.86	37.19
average depth (m)	0.51	0.52	0.31	0.54	0.26	0.41
maximum depth (m)	0.74	1.06	0.64	0.84	0.44	0.66
average velocity (m/s)	0.56	0 21	0.75	0.51	0.43	0.53
maximum velocity (m/s)	1.29	1.09	1.19	0.9	0.86	1.05
measured area (m^2)	9.49	21.74	14.73	29.17	14.94	16.49
discharge (cms)	5.12	7.05	15.06	15.51	8.87	11.15
D_{16} bar (m)	0.013	0.011	0 017	0.015	0.015	0.017
D_{50} bar (m)	0.032	0.055	0.042	0.029	0.053	0.033
D_{84} bar (m)	0.074	0.092	0.074	0.044	0.111	0 063
ratio D84/D16 bar	2.42	2.90	2.09	1.72	2.72	1.93
D_{50} net (m)	0.0049	0.0051	0.0050	0.0050	0.0045	0.0048
# grains in net	62	39	151	10	30	25
% sand	10	15	10	20	15	20
Slope	0.000302	0.000302	0.000393	0.000393	0.000397	0.000397
Computed Values						
bankfull width (m)	90.83	87.48	74.07	108.2	97.23	157.28
max. depth at bankfull (m)	14.07	7.82	3.1	5.91	9.85	7.97
avg. velocity at bankfull (m)	0.69	1.2	2.24	0.85	0.58	0.58
area at bankfull ($m^{2)}$	767.59	443.67	165.56	435.02	730.18	726.08
bankfull discharge (cms)	530.84	530.84	370.08	370.08	426.03	421.72
	h_{bf} (m)	**Q_{bf} (cms)**				
Austin Gauge	4.88	515.38				
Bastrop Gauge	4.27	430.33				

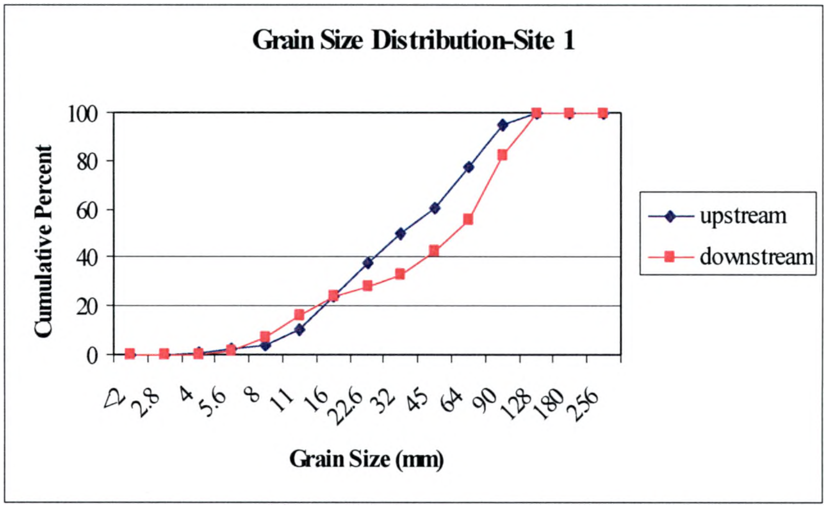

Figure 25: Comparison of grain size distribution at Site 1. Average grain size at Site 1A (upstream) is finer than at Site 1B (downstream).

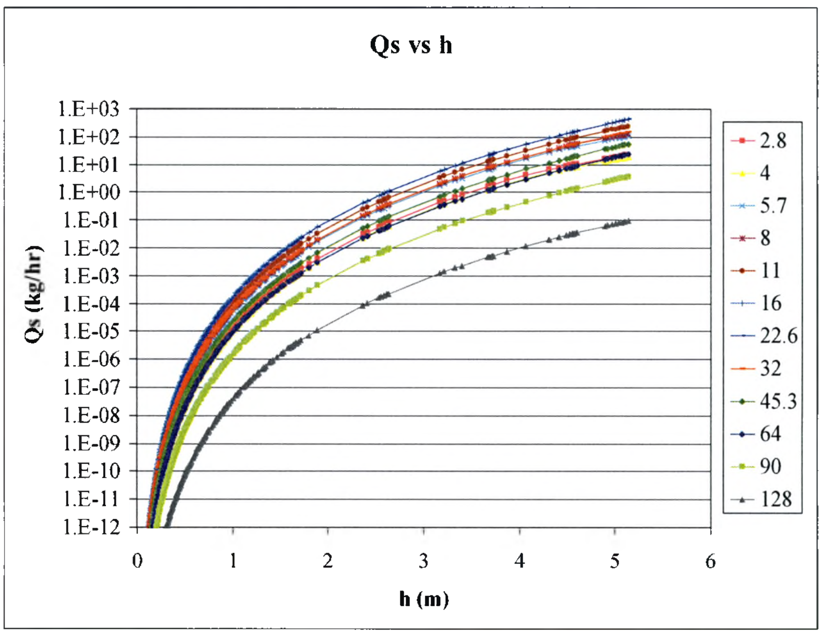

Figure 26: Sediment transport rates compared to depth over gravel bar at Site 1A. Transport rates are divided by different size classes.

Table 3: Total amount of sediment transported (kg/hr).						
Depth (m)	**1A**	**1B**	**2A**	**2B**	**3A**	**3B**
1	6.98E-04	2.55E-05	7.31E-04	2.40E-02	3.99E-04	1.68E-02
2	0.87	0.03	0.03	12.53	0.19	9.01
3	18.05	0.70	1.19	534.83	7.07	325.54
4	185.77	6.98	16.69	4980.28	98.84	3750.04
5	1192.18	51.42	111.97	19644.03	734.39	17106.21
6	na	na	451.62	51316.38	3309.85	48926.24
7	na	na	1321.34	103792.29	10258.21	105826.37

Table 4: Estimated values of discharge and return period associated with various depths of flow.						
	1A	**1B**	**2A**	**2B**	**3A**	**3B**
Height Over Bar (m)	**over 5**					
Corresponding Q (cms)	742	750	753	871	683	759
Return Period (years)	1.46	1.03	0.76	1.49	0.51	1.04
Height Over Bar (m)	**4 to 5**					
Corresponding Q (cms)	589	588	576	705	532	648
Return Period (years)	0.46	0.23	0.33	0.39	0.28	0.36
Height Over Bar (m)	**3 to 4**					
Corresponding Q (cms)	394	418	420	513	375	486
Return Period (years)	0.30	0.15	0.23	0.27	0.20	0.25
Height Over Bar (m)	**2 to 3**					
Corresponding Q (cms)	285	297	293	345	221	340
Return Period (years)	0.24	0.12	0.15	0.19	0.12	0.16
Height Over Bar (m)	**1 to 2**					
Corresponding Q (cms)	134	149	150	219	111	199
Return Period (years)	0.08	0.04	0.06	0.10	0.03	0.09
Height Over Bar (m)	**0 to 1**					
Corresponding Q (cms)	39	46	41	85	14	72
Return Period (years)	0.01	0.01	0.01	0.09	0.00	0.02

Site 1B *[30°12'58.07" N, 97°36'24.01" W; WGS84 Datum]*

Selection of Site 1B was challenging because of an active mine immediately downstream of the 1991 avulsion. Gravel excavation and a loss of riparian vegetation at this active mine has caused an influx of sediment into the river, which filled the channel with fine material, resulting in a soft bottom not representative of the river at a more "natural" state (Figure 22). Because of the proximity of active mining, measurements were taken at a riffle just upstream of the active site, but downstream of the confluence of the active channel with the abandoned channel (Figure 27).

Figure 27: Confluence between the main channel (prior to avulsion) and the new channel (after avulsion). Photo by author.

As with Site 1A, two cross sections were measured at this location to show channel bathymetry and discharge. The water was clear enough to observe hiding. Flow measurements were compared to the Austin gauge, and found to be an average of 3% less than the discharge at Austin, and ranged from 18% greater than to 23% less than the flow at Austin. The high degree of variability at this site is likely due to differences in the amount of flow contributed from the old channel.

The channel is 37.5 meters wide and 1.06 meters deep at the thalweg. Average velocity is 0.21 m/s, and 1.09 m/s in the thalweg. Bankfull width and depth are estimated to be 87.5 meters and 7.8 meters, respectively. Sediment along the bar has a distinct bimodal sorting. Average grain size of the bar adjacent to the riffle is 55 mm. Amount of sand is estimated to be 15%. Average diameter of grains caught in the net is 5mm.

The amount of sediment transported at different depths of flow for each size fraction, based on pebble count data is modeled in Figure 28. The most mobile sediment size at this site is 11 mm, and the least mobile is 128 mm. Sediment transport rates for all grain sizes at Site 1B were modeled for depths between 1 m and 5 m over the gravel bar, and ranged from 0.00003 kg/hr to 51.42 kg/hr (Table 3). Discharge rates (Table 4) range from 149 cms to 750 cms for depths between 1 m and 5 m. The return periods associated with these rates are approximately 15 days to 1.03 years.

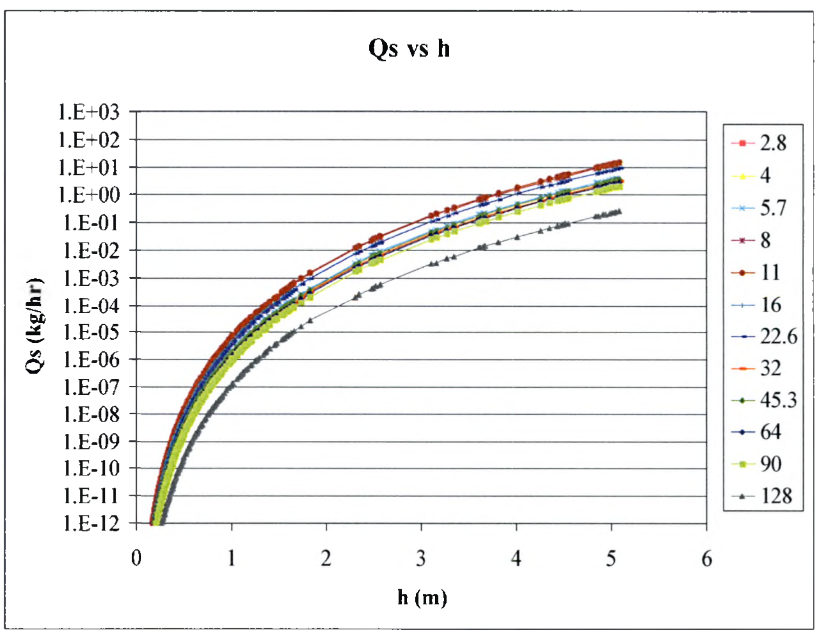

Figure 28: Sediment transport rates compared to depth over gravel bar at Site 1B. Transport rates are divided by different size classes.

Site 2A *[30°12'34.57" N, 97°33'45.47" W; WGS84 Datum]*

Aerial photographs in Figure 29 show the upstream and downstream locations of the cross sections taken (yellow line) and pebble counts conducted (red X). Site 2A is along a riffle at the top of a small meander bend. The bed is comprised of mixed gravel and bedrock, and is the only location selected with bedrock dominating part of the channel.

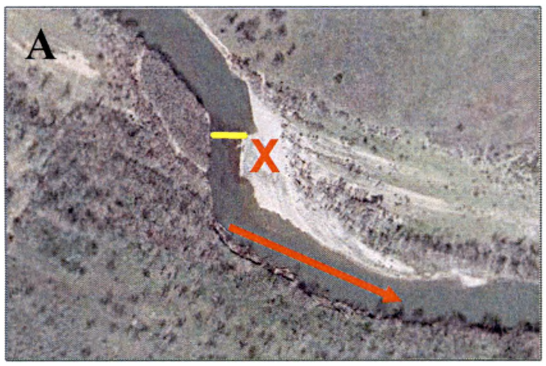

Figure 29: Location of cross section measurements and pebble counts for Site 2A (A) and Site 2B (B). From Google Earth version 3.0.0762.0.

Cross sections were measured at two different times to illustrate channel bathymetry and gather discharge data. This site is most closely related to the Bastrop gauge, downstream of all study sites. Flow measurements compared to the Bastrop gauge were found to be an average of 14% less than at Bastrop, but ranged from 10-18% under Bastrop flow. Gilleland, Wilbarger, and Big Sandy Creeks all discharge into the Colorado River between Site 2A and the Bastrop gauge, likely accounting for a portion of the higher flow at Bastrop.

The channel is 49 meters wide and 0.64 meters deep at the thalweg. Average velocity is 0.75 m/s, and 1.19 m/s in the thalweg. Bankfull width and depth are estimated to be 74 meters, and 3.1 meters, respectively. Average grain size along the bar is 42 mm

(Figure 30). Sand is estimated to comprise 10% of all surface sediment. Average diameter of grains caught in the net is 5mm.

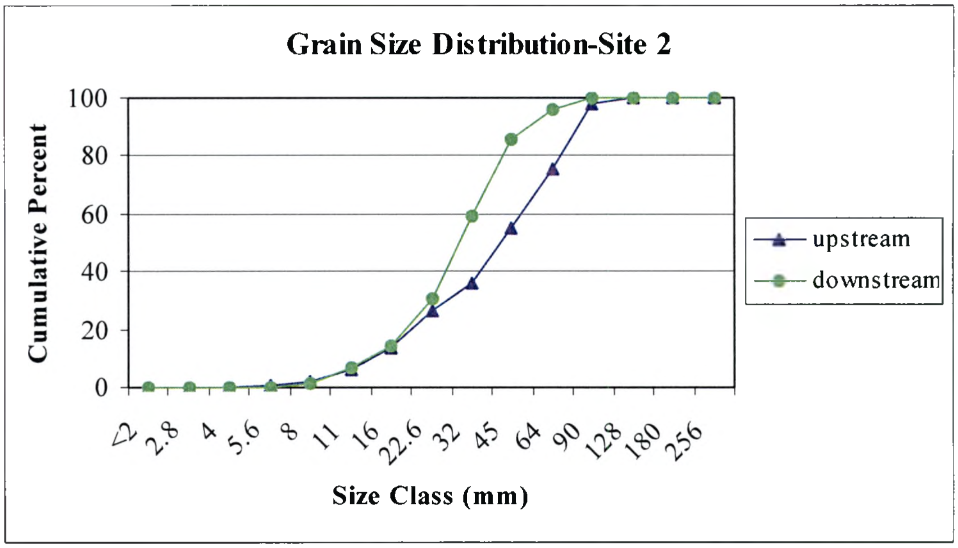

Figure 30: Comparison of grain size distribution at Site 2. Average grain size at Site 2A (upstream) is coarser than at Site 2B (downstream).

Based on sediment transport rates associated with different flows (and corresponding depths), the most mobile size fraction varies with flow, but is between 11 mm and 45.3 mm (Figure 31). The least mobile size fraction is 128 mm. Rate of total sediment transport at Site 2A was modeled to be 0.0007 kg/hr to 112 kg/hr, with depths ranging from 1 m to 5 m over the gravel bar (Table 3). Discharge rates for the same depths range from 150 cms to 753 cms. The return periods associated with these rates are approximately 22 days to 277 days (Table 4).

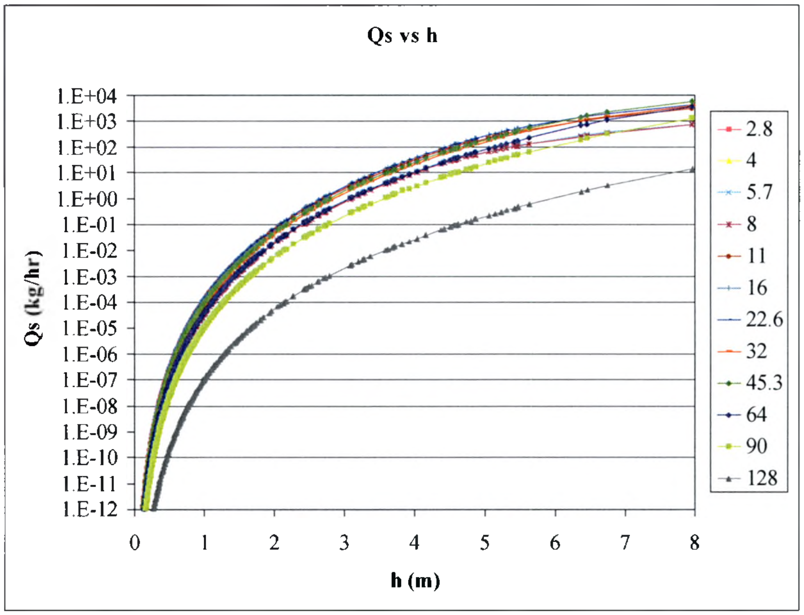

Figure 31: Sediment transport rates compared to depth over gravel bar at Site 2A. Transport rates are divided by different size classes.

Site 2B *[30°13'12.76" N, 97°31'31.69" W; WGS84 Datum]*

The downstream location for Site 2 (where the river avulsed between 1973 and 1984) is highly influenced by a very recent break (January 2007) in the barrier between one of the settling ponds from an abandoned gravel mine and the active channel (Figure 32). The initial purpose of this project was to study several sites influenced by gravel mines at different stages (active, recently avulsed, avulsed long ago). This site was selected as the oldest (avulsion occurred over 20 years prior) to see how long the system takes to re-establish some form of equilibrium. It was selected prior to the recent break. No other site that was shallow enough to measure and compare to upstream of the old avulsion (Site 2A) was available between downstream of the old avulsion and upstream of the breach. While the breach precludes the use of this site as a measure of channel recovery from an old avulsion, it provides useful insight into the process of channel avulsion through abandoned mine pits. The sampling sites were maintained in this location with the new purpose of documenting the process of avulsion.

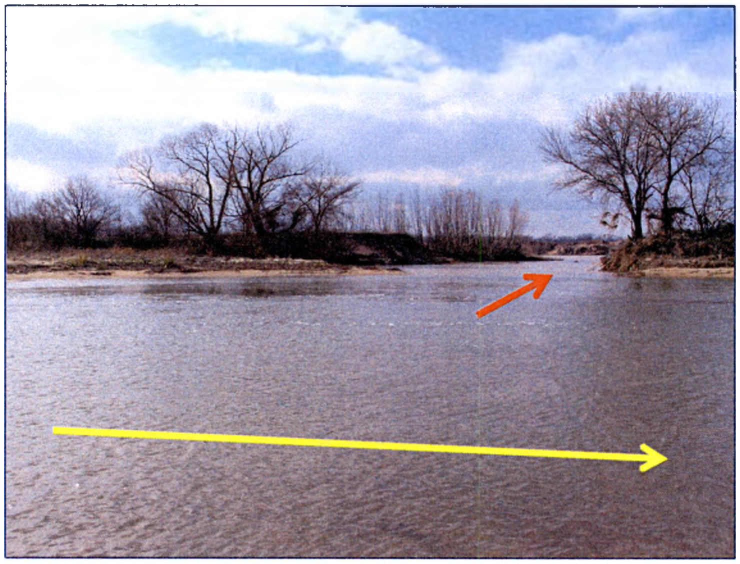

Figure 32: Break in buffer at Site 2B. A recent breach between the main channel (flow direction shown by yellow arrow) and a pond associated with an active mine (break shown by red arrow) occurred during the course of this study. Photo by author.

Two cross sections were measured at this location to show channel shape and obtain discharge rates. Flow measurements at Site 2B were compared to the Bastrop gauge, and averaged 14% less than at Bastrop, but ranged from 8-20% lower. Wilbarger and Big Sandy Creeks feed into the Colorado River between this site and the Bastrop gauge, probably accounting for some of the difference in flow.

The channel is 52.1 meters wide and 0.84 meters deep at the thalweg. Average velocity is 0.51 m/s, and 0.9 m/s in the thalweg. Bankfull width and depth are estimated to be 108.2 meters, and 5.91 meters, respectively. Average grain size of the bar adjacent to the riffle is 29 mm. Percent sand on the surface is estimated at 20%. Average diameter of grains caught in the net is 5 mm.

A comparison of sediment transport rates to discharge and corresponding depth is shown in Figure 33. The most mobile sediment size at this site is 32 mm, and the least mobile is 90 mm (this was the largest size grain collected in the pebble count at this site). The rate of transport for all size fractions at Site 2B ranged from 0.024 kg/hr to 19644 kg/hr for depths between 1 m and 5 m over the gravel bar (Table 3). Corresponding discharge rates range from 219 cms to 871 cms. The return periods associated with these rates are approximately 37 days to 1.49 years (Table 4).

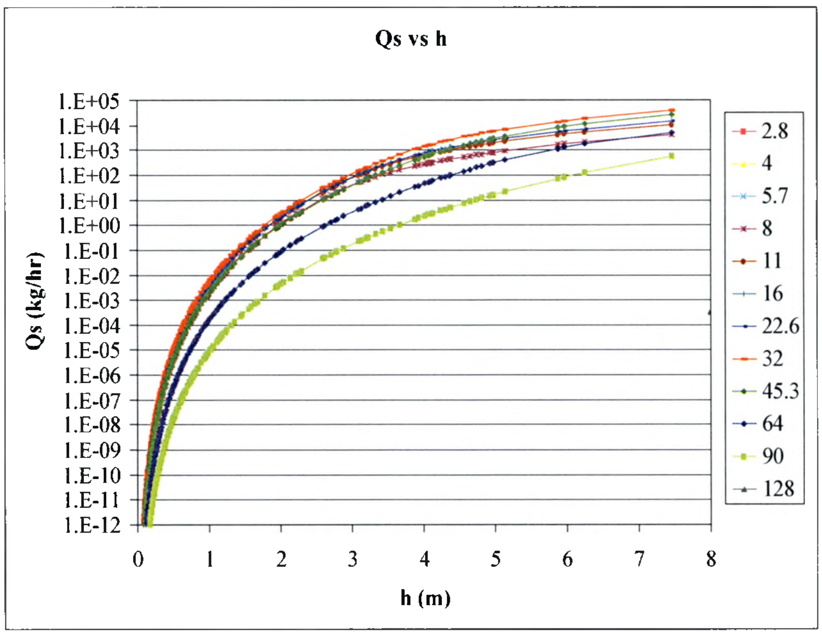

Figure 33: Sediment transport rates compared to depth over gravel bar at Site 2B. Transport rates are divided by different size classes.

Site 3A *[30°12'40.93" N, 97°30'48.46" W; WGS84 Datum]*

Aerial photographs in Figure 34 show the upstream and downstream locations of cross sections taken (yellow line) and pebble counts conducted (red X). This site is upstream of a large gravel mine that is flooded during high flow, but not directly in contact with the river under average flow conditions (has not avulsed). There was a breach in the buffer between a gravel pit and the main channel in June of 2007, which was rapidly repaired by the excavation company (Kevin Anderson, personal communication). The upstream location of the third study site is the widest section of channel of any of the sites. This site is also the straightest reach of river both upstream and downstream. There is a highly bimodal distribution to the sediment (Figure 35).

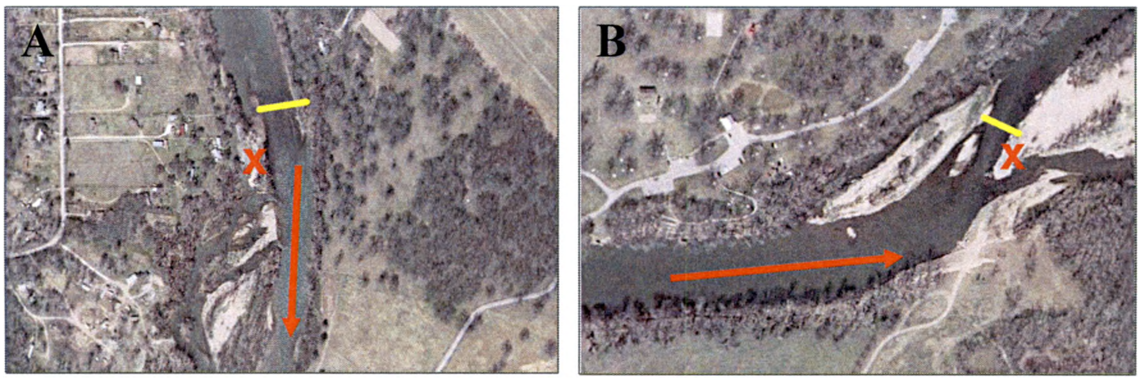

Figure 34: Location of cross section measurements and pebble counts for Site 3A (A) and Site 3B (B). From Google Earth version 3.0.0762.0.

Figure 35: Gravel bar at Site 3A. This site has a distinctly bimodal distribution of grains. Photo by author.

Three cross sections were measured at this location to show channel bathymetry and obtain discharge data. Flow measurements were compared to the Bastrop gauge, upstream of this site, and averaged to be 1% less than the discharge at Bastrop. However, discharge ranged from 13% under to 4% over that of Bastrop. As with Site 2B, Wilbarger and Big Sandy Creeks discharge into the Colorado River between this site and Bastrop, contributing a variable amount of flow.

Field measurements, including width, depth, velocity, discharge, average grain size, and percent sand, as well as calculated values for the channel at bankfull are summarized in Table 2. The channel is 54.86 meters wide and 0.44 meters deep at its thalweg. Average velocity is 0.43 m/s, and 0.86 m/s in the thalweg. Bankfull width and depth are estimated to be 97 meters and 9.85 meters, respectively. Average grain size of the bar adjacent to the riffle is 53mm (Figure 36). Percent sand is estimated to be 15%. Average diameter of grains caught in the net is 4.5 mm.

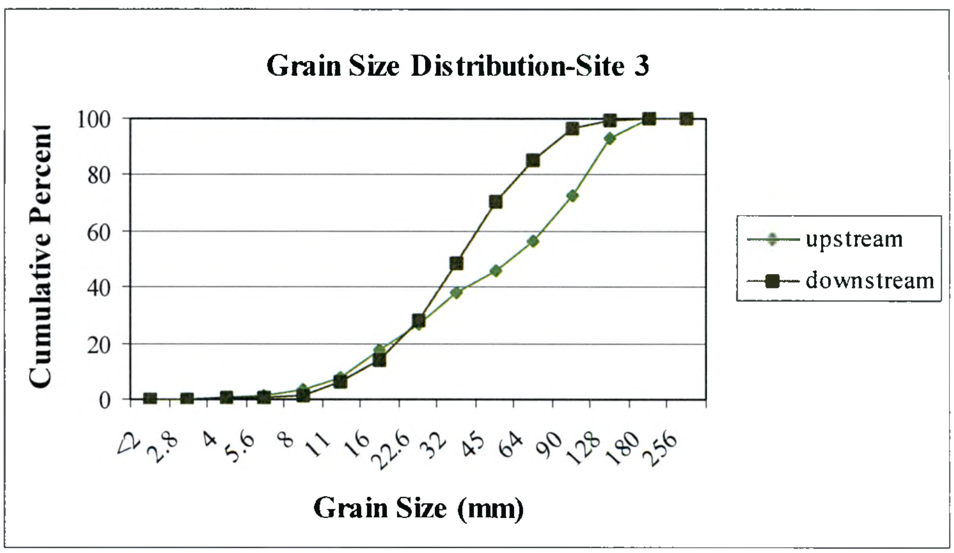

Figure 36: Grain size distribution of Site 3A (upstream) and Site 3B (downstream). Average grain size at Site 2A (upstream) is coarser than at Site 2B (downstream).

The amount of sediment transported at various discharges shows the most mobile size fraction to be 16 mm to 22.6 mm, and the least mobile 180 mm (Figure 37). The total rate of transport at Site 3A was modeled to be between 0.0004 kg/hr to 734 kg/hr for depths ranging from 1 m to 5 m over the gravel bar (Table 3). Discharge rates for the same depths are 111 cms to 683 cms. The return periods associated with these rates at this site are approximately 11 days to 0.5 years (Table 4).

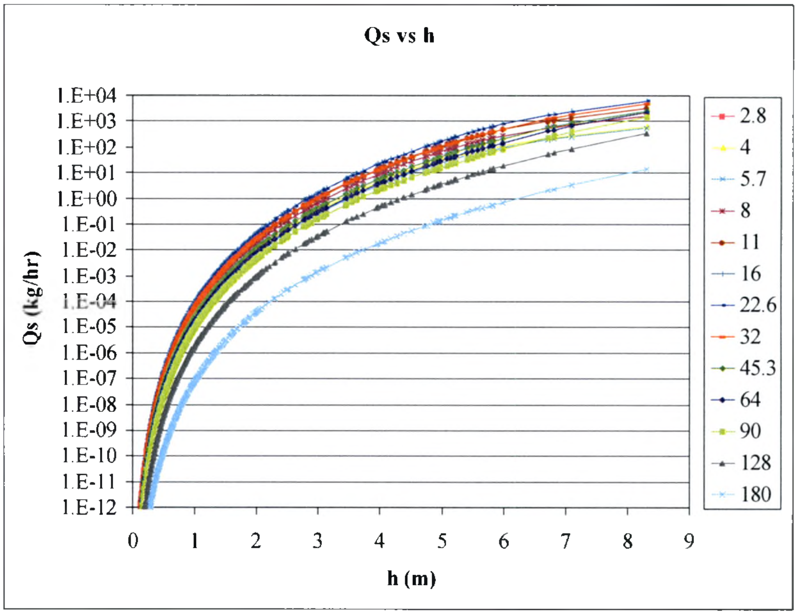

Figure 37: Sediment transport rates compared to depth over gravel bar at Site 3A. Transport rates are divided by different size classes.

Site 3B *[30°12'36.94" N, 97°29'42.57" W; WGS84 Datum]*

Site 3B is at a riffle downstream of a large meander bend. Imbricated pebbles are observed on the gravel bar (Figure 38). There is an island on the left side of the channel with some flow between the island and left bank. The right side of the channel has a large gravel bar that forms an island under higher flows. The heterogeneity in the shape of the channel will significantly affect bankfull measurements incorporating area and discharge.

Four cross sections were measured at this location to show channel bathymetry and discharge. Flow measurements were compared to the Bastrop gauge, and averaged 2% less that the discharge at Bastrop. Flow measurements were highly variable at this site, ranging from 20% under to 29% over the flow at Bastrop. Factors other than variable inflow from contributing streams must affect the discharge rates between this site and the Bastrop gauge. Changing volumes of flow around the island is one reason for the large degree of variability.

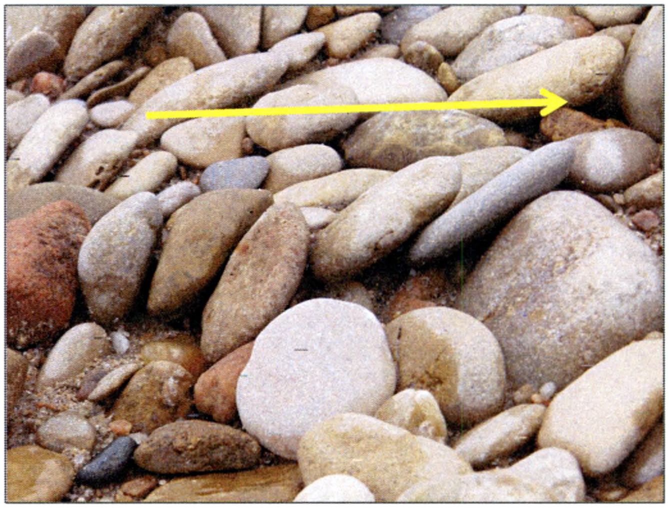

Figure 38: Well imbricated pebbles along the gravel bar at Site 3B. Yellow arrow shows direction of flow. Photo by author.

The channel is 37.19 meters wide and 0.66 meters deep at the thalweg. Average velocity is 0.53 m/s and 1.05 m/s in the thalweg. Bankfull width and depth are estimated to be 157.28 meters and 7.97 meters, respectively. Average grain size of the bar adjacent to the riffle is 33 mm. Percent sand on the bar is estimated to be 20%. Average diameter of grains caught in the net is 4.8 mm.

Sediment transport data for Site 3B (Figure 39) shows the most mobile size fraction varies somewhat with flow, but is generally 32 mm, with 16 mm close or overlapping at many flows. The least mobile size sediment is 128 mm. The total sediment transport rate for all grain sizes at Site 3B were modeled for depths of 1 m to 5 m over the gravel bar, and ranged from 0.0168 kg/hr to 17106 kg/hr (Table 3).

Corresponding discharge rates range from 199 cms to 759 cms for depths between 1 m and 5 m. The return periods associated with these rates are approximately 33 days to 1.04 years (Table 4).

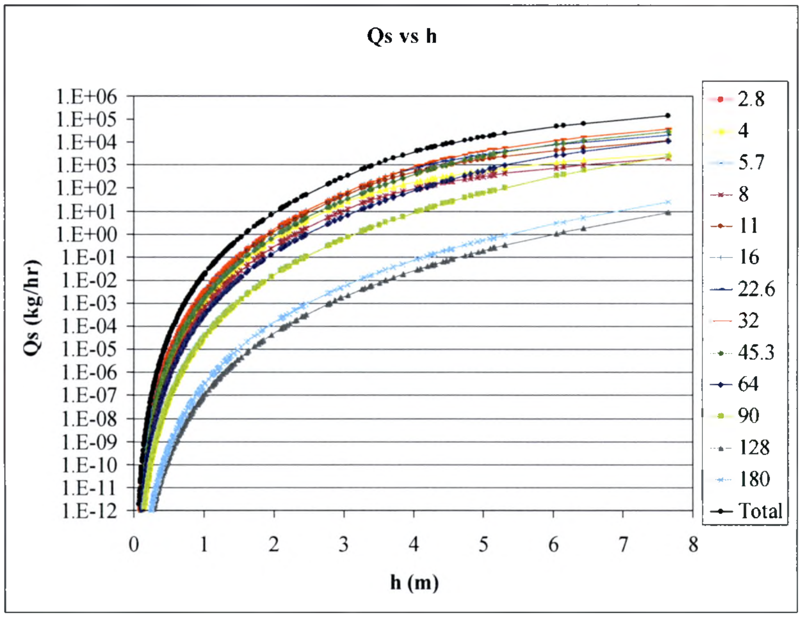

Figure 39: Sediment transport rates compared to depth over gravel bar at Site 3B. Transport rates are divided by size class.

CHAPTER VII

DISCUSSION

Observations can be made about the processes affecting sediment transport associated with gravel extraction, breaches in the bank, and river avulsion by comparing results from a site upstream of a gravel mine to those downstream. Evaluating results between sites, where the river changed course at different times, allows for insights into how time factors into the river's ability to rework sediments in the channel and establish an equilibrium more closely associated with channel dynamics prior to the avulsion.

Grain Size

Grain size distribution indicates the supply of sediment available to the channel, as well as the transport capacity of the river. When comparing the D_{50} of the gravel bars, Sites 2 and 3 both exhibit a fining trend from upstream to downstream (Table 2). In contrast, Site 1 coarsens from upstream to downstream. This is the site of the most recent avulsion and the coarsening trend could be associated with the new source of gravel available to the river as a result of the avulsion. This site is also the most poorly sorted of all sites. A lack of sorting is indicative of immature sediment, or reworking of nearby sediment. Difference in slope among sites is less than 0.0001, and should not be a significant factor in variations in transport.

D_{16} values (indicating one standard deviation below the mean) are within a full ϕ unit among sites. There is a slight fining trend upstream to downstream at Sites 1 and

2, and a slight coarsening trend at Site 3. These differences in size fractions of sediment do not reveal much about the trends of movement within or between sites.

D_{84} values (one standard deviation above the mean) reveal a little more about what is available for transport under high flows at each site. These values support the D_{50} trend of downstream fining at Sites 2 and 3, and downstream coarsening at Site 1.

The D_{84} at Site 2B (44 mm) is the finest of all sites. This site also has the most well sorted sediments (least variability in size), as indicated by the ratio of D_{84} to D_{16}. Site 2B is downstream of the oldest breached gravel pit in this study. The finer, more homogeneous nature of the sediment most likely relates to sediment supply. After the avulsion, coarser sediment typically mobilized during high flows would deposit into the breached pit (which is likely deeper and wider than the original channel), and not transported downstream. High flows continue to mobilize and transport the larger sediment already located downstream of the avulsion, thereby homogenizing the gravel bar and depleting it of the coarser size fractions.

The D_{84} grain size of Site 3A is the largest of any site (110.9 mm). This locale shows a bimodal distribution and is among the least sorted. As mentioned earlier, Site 1B also has a bimodal distribution, which is likely associated with new sediments available from the avulsion, as well as sediment transported by the former main channel and current main channel.

Sediment Transport-Gravel Bars

The surface-based transport model of Wilcock and Crowe was used to estimate sediment movement at each site. Model input parameters are flow depth, grain size, slope, and percent sand. When compared to the upstream sampling at each reach, all locations show an increase in sand at the downstream site (Table 2). This increase is associated with finer material, reworked from the mines, that is carried into the river by runoff or inundation of the mines at high flows. An increase in sand increases transport rates of the gravel fraction of bedload sediments (Curran and Wilcock 2005). The increase in the fraction of sand on the downstream gravel bars of Sites 2B and 3B, as well as the decrease in average grain size is consistent with an increase in transport capacity. Site 1 has a higher sand content downstream (1B), but its overall sediment is much coarser than upstream (1A). The downstream coarsening is consistent with a decreased transport capacity. The sand content at Site 1B increases to 15% of the bed surface, which is not high enough to significantly affect gravel transport. The most mobile size fraction for all sites ranges from 11 mm to 45.3 mm. The least mobile is 128 mm, except for Sites 2B (90 mm) and 3A (180 mm).

Site 2B shows the least variability in gravel sizes as well as in transport rates. This site has the highest percent of sand and the largest difference in sand content when compared to the upstream site (2A). The elevated sand content at this location is largely associated with a breach in an active gravel pit in January of 2007. Based on the model, this site has the capacity to move the largest amount of sediment. This is a reflection of the large amount of sand on the surface and the relative homogeneity in sediment size (when compared to other sites). Hiding is reduced on a relatively uniform sediment bed, which in turn leads to a more uniform rate of transport. Calculated transport rates are likely to differ greatly from actual transport rates, because of the recent breach into an active pit. The breach has opened the main river to a large pond, and changed the flow characteristics in the area. Discharge rates and associated depths are affected, because there is now a large open pond for water to flow in and out of, essentially acting as a reservoir to hold water and lower flow depths downstream. Lower river depths will transport less sediment.

Total transport rates at each site, based on depth of water over the gravel bar, are shown in Table 3. Transport rates of all upstream sites are within one order of magnitude of each other. Sand comprises 10% of the sediment at Site 1A and Site 2A, and 15% at Site 3A. Downstream Sites 2B and 3B contain approximately 20% sand, transport significantly more sediment than upstream, and are generally within the same order of magnitude as each other. Site 1B (15% sand) transports less sediment than upstream, and significantly less than the other downstream sites (related to the coarsening trend, rather than fining trend, from upstream to downstream). The high sand contents at Site 2B and 3B are likely a result of recent breaches between mining ponds and the main channel. The lower sand content at Site 1B could indicate the system has had enough time to flush out some of the finer material since the avulsion occurred (between 1973 and 1984).

Sediment Transport-Channel Bed

Modeled rates of transport were compared to measured rates of transport in the channel under relatively low flow conditions (7 cms to 17 cms). The data are derived from the amount of sediment captured in the portable bedload traps placed on the channel bed over a 24 hour period, and compared to calculated values based on the transport model using the same discharge rates and corresponding depths. For the calculations, the grain size distribution and percent sand was assumed to be analogous to what was observed on the gravel bars at each site, since a pebble count was not feasible in the swift current and the water was not always clear enough to see through to estimate percent sand. Because of flow variations over the 24 hour period the nets were left out, a maximum and minimum rate of transport was calculated based on the highest and lowest discharge values for that 24 hour period.

Actual transport rates were one to two orders of magnitude greater than calculated values at Site 1A, and two to four orders of magnitude greater at Site 1B. Actual transport rates at Site 2A were one order of magnitude greater than values based on the model, and two to three orders of magnitude less than values from the model at Site 2B. Site 3A was within the same order of magnitude to one order greater than the model, and one to two orders of magnitude less than the model at Site 3B (Table 5).

All three upstream sites exhibited roughly one order of magnitude greater actual transport rates than calculated transport rates. These were the sites unaffected by gravel mining. Sites 1B and 2B showed the greatest difference between actual and calculated rates. Site 1B was downstream of the oldest avulsion, and had actual rates of transport two to four times greater than calculated rates based on the model. This discrepancy could be associated with the time period the nets were left (longer sampling time could yield more accurate results). Most of the sediment was between 2.8 mm and 8 mm, but one 22.6 mm grain size was trapped and may have skewed the results. Actual rates at Site 2B were two to three orders of magnitude less than calculated rates. This is the site with a recent avulsion, which made accurate measurements impossible. A considerable amount of sand being transported through the system at Site 2B was not captured by the nets.

Table 5: Expected and actual rates of transport.

	2.8	4	5.6	8	11	16	22.6	32	45	64	90	128	180	Total
Expected Rates of Transport from SBTM kg/hr														
1A min	9.49E-08	7.1E-08	3.75E-07	4.45E-07	7.48E-07	1.26E-06	8E-07	4.4E-07	1.57E-07	6.71E-08	1.05E-08	2.62E-10		4.47E-06
1A max	1.06E-06	7.9E-07	4.17E-06	4.94E-06	8.32E-06	1.4E-05	8.9E-06	4.89E-06	1.75E-06	7.47E-07	1 17E-07	2.92E-09		4 97E-05
1B min	0	0.00	0.00	1.75E-08	1.94E-08	1.13E-08	5E-09	3.92E-09	4.76E-09	3.42E-09	2.6E-09	3.3E-10		7.34E-08
1B max	0	0.00	0.00	2.95E-07	3.26E-07	1.9E-07	8.4E-08	6.6E-08	8.02E-08	5.75E-08	4.37E-08	5.55E-09		1.24E-06
2A min	0	0	1.06E-05	9.83E-06	3.14E-05	3.65E-05	4.6E-05	2.15E-05	2.49E-05	1.04E-05	2.81E-06	2.73E-08		1.94E-04
2A max	0	0	4.73E-05	4.37E-05	0.000139	0.000162	0.0002	9.54E-05	0.000111	4.63E-05	1.25E-05	1.21E-07		8.61E-04
2B min	0	0	0	0.00056	0.001053	0.001098	0.0016	0.001519	0.000534	4.43E-05	2.32E-06	0		6.41E-03
2B max	0	0	0	0.002489	0.004677	0.004879	0.00709	0.006751	0.002372	0.000197	1.03E-05	0		2.85E-02
3A min	0	3.7E-06	2.76E-06	7.63E-06	1.22E-05	1.85E-05	1.2E-05	1.11E-05	4.67E-06	3.16E-06	1.79E-06	3.95E-07	1.6E-08	7.83E-05
3A max	0	2E-05	1.53E-05	4.25E-05	6.79E-05	0.000103	6.9E-05	6.19E-05	2.6E-05	1.76E-05	9.95E-06	2.2E-06	8.7E-08	4.36E-04
3B min	0	0.00025	0	0.000115	0.00051	0.000671	0.00076	0.000675	0.000317	6.22E-05	6.76E-06	2.06E-08	5.8E-08	3.36E-03
3B max	0	0.00138	0	0.000641	0.002836	0.003736	0.00421	0.003759	0.001762	0.000346	3.76E-05	1.15E-07	3.2E-07	1.87E-02
Actual Rates of Transport based on Sediment Captured in Nets (kg/hr)														
	2.8	**4**	**5.6**	**8**	**11**	**16**	**22.6**	**32**	**45**	**64**	**90**	**128**	**180**	**Total**
1A	0	1.3E-05	0.000196	0.000183	6.67E-05	0	0	0	0	0	0	0	0	4.58E-04
1B	4.17E-07	1.3E-06	0.000121	0.000138	0	0	0.00044	0	0	0	0	0	0	6.98E-04
2A	0	5.8E-05	0.000454	0.000525	0.000458	0	0.00042	0	0.003829	0	0	0	0	5.75E-03
2B	0	1.3E-06	1.67E-05	0.00005	0	0	0	0	0	0	0	0	0	6.79E-05
3A	8.33E-07	2.1E-05	9.58E-05	2.92E-05	0	0	0	0	0	0	0	0	0	1.47E-04
3B	4.17E-07	8.3E-06	0.000075	0.00005	0.000075	0	0	0	0	0	0	0	0	2.09E-04

Another factor accounting for the discrepancy between actual and modeled rates of transport was the large number of clay clasts trapped in the nets. These clasts have a lower specific gravity, which would result in a smaller reference shear stress, and increased transport capacity. Since calculations are based on the specific gravity of the sediment to be 2.65, a larger proportion of the sediment with a significantly lower specific gravity would have an affect on modeled transport rates. For example, Site 2B has one of the largest percent of clay clasts as well as a large discrepancy between modeled and actual transport rates. This site also has the fewest number of overall grains, which could be a factor by increasing the importance of each individual grain captured. Interestingly, Site 1B has the greatest discrepancy, yet did not contain any clay clasts (Table 6). This could indicate the difference in overall specific gravity is not a significant factor, or there are other over-riding forces affecting the outcome.

Table 6: Number of clay clasts compared to total number of grains caught in net.

Grain Size (mm)	1A	1B	2A	2B	3A	3B
2.8		0/1 (0%)			0/2 (0%)	0/1 (0%)
4	2/7 (29%)	0/2 (0%)	5/22 (23%)	1/2 (50%)	1/8 (13%)	0/4 (0%)
5.6	7/43 (16%)	0/25 (0%)	16/86 (19%)	1/5 (20%)	1/17 (6%)	1/16 (6%)
8	3/10 (33%)	0/10 (0%)	7/31 (23%)	0/3 (0%)	0/3 (0%)	0/3 (0%)
11	0/2 (0%)		1/10 (10%)			0/1 (0%)
16						
22.6		0/1 (0%)	0/1 (0%)			
32						
45			0/1 (0%)			

CHAPTER VIII

CONCLUSION

The purpose of this study is to look at how breaches in the buffer between gravel pits and the main stem river, and subsequent avulsions initiated by such breaks, affect fluvial processes, particularly bedload transport. The increased sand content supplied to the river downstream of the gravel pits was hypothesized to increase transport of sediment at these sites. A reduction in sediment size was also expected downstream of avulsed sites, because larger grains would drop out of transport into the deep pits, which were now part of the main channel. Excess shear stress in the channel would mobilize sediment downstream of the former pit, resulting in erosion of channel bars and the channel bed.

An ideal control site would be an undisturbed meander bend, with riffles upstream and downstream. This would allow for measurements of more natural trends in grain size distribution, as well as sand content. Unfortunately, floodplain mining is so extensive in this region that such a site does not exist. Rather, a site of active mining where the channel has not permanently avulsed through the gravel pits was used (Site 3).

The assumed trends of increased transport rates, increased sand content, and decreased sediment size from upstream to downstream was observed at Site 2, but not at Site 1 (which was coarser downstream of the mine). These findings were expected to be more likely at Site 1, because it is a more recent break. However, the influence of current mining activity, as well as measurements taken so close to the confluence between the old and new channel are possible reasons for the difference in expected results.

Transport rates (based on the model) were not comparable downstream of the sites with avulsions that occurred at different times (1B and 2B), since Site 1B was significantly coarser, and therefore was an overriding factor in transporting less sediment. A comparison of Site 2B (the oldest avulsion) to Site 3B (which had no permanent avulsion), shows similar trends in downstream fining, and they have approximately the same percent sand. These sites also had comparable transport rates, and could be in similar states of stability. These similarities could also be associated with recent (or potentially frequent) breaches at both sites. Frequent measurements at these sites, as well as other comparable sites, would allow for a better assessment of whether or not the river has "recovered" from the avulsion which occurred 20 to 30+ years ago.

Studying various sites allowed for observations of channel modification at different times after an avulsion. Site 1 had a permanent break approximately 16 years ago. Site 2 changed path sometime between 23 and 34 years ago. Site 3 has not had a permanent avulsion, but did have a recent breach associated with flooding, which was quickly repaired by the mining company. The repaired breach still allows water to flow in and out of the site, but prevents boaters from entering the pond. Because of recent breaches and differences in downstream grain size trends, significant conclusions could not be made concerning the time frame necessary to establish a new equilibrium. Upstream to downstream trends were more easily observed than trends between sites.

As mentioned, two of the sites experienced breaches in 2007 (Sites 2B and 3B). The breach at Site 2B was directly upstream of where the cross sections were measured and sediment nets positioned. The breach at Site 3 was between the upstream and downstream sites, hundreds of meters upstream of the measurements at Site 3B. One of the initial objectives of this study was to compare recovery times after an increase in sand was introduced into the channel, associated with an avulsion. Since the "control" site and the site of the oldest avulsion both had recent breaches, which contributed large amounts of sand into the channel, attempting to study the recovery time after an avulsion was not possible.

Qualitative observations were noted with the aid of topographic maps and aerial photographs. Expected trends were found, such as when an operation grows over time, less riparian vegetation is observed, and there is an observable increase in runoff, carrying finer sediment that is deposited in the river. Mines along straight reaches of the river were less likely to experience breaches or avulsions than operations along meander bends. Areas downstream of active mines had increased levels of turbidity in the water, and soft beds which were not representative of areas along the river not impacted by mining.

Quantitative findings were estimated using pebble counts, flow measurements, gauge data, bedload traps, and the transport model of Wilcock and Crowe (2003). The increased sand content downstream of mines was generally associated with increased transport capacity. Transport rates downstream of Site 3B were calculated for various amounts of sand, signifying a breach in the pit and influx of fines downstream (Figure 40). The increase in transport rates is generally thought to correspond to a change from a framework to matrix dominated bed.

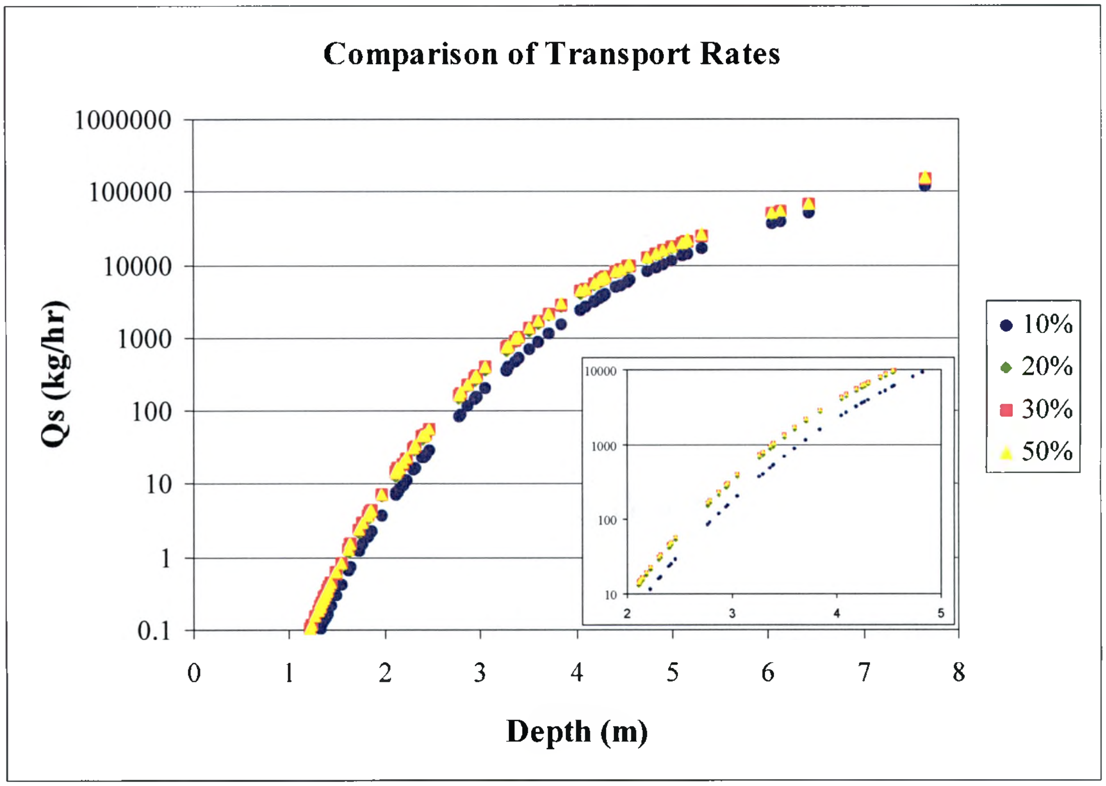

Figure 40: Sediment transport rates based on percent sand on the channel bed for Site 3B. Note the increase in movement between 10% sand and higher percentages (20% to 50%) on the bed surface.

Actual transport rates, based on grains caught in the portable traps, showed little difference between upstream and downstream sites, or between sites. This is likely associated with the low flow conditions on the Colorado River during much of the sampling period for this project. Higher flows with a capacity to transport larger grains may have shown a trend of increased transport with increased sand content, but conditions were not favorable to evaluate movement at higher rates of discharge.

While a distinction cannot be made between the reasons for discrepancies in actual transport rates compared to those estimated by the model, it is important to be aware of potential causes of these discrepancies, both in the field and from assumptions built into the model. There are several factors relating to field measurements which could be potential sources of error. Since it was not always possible to put the sediment nets in the thalweg, they were often placed in other parts of the channel. Ideally, nets would be set across the entire width of the river to give a more complete picture of the spatial variability in transport in the channel. Other issues include the rough estimate of sand in the channel, based on the percent sand along the nearby bars. The water was typically too muddy to make a visual estimate of the amount of sand on the channel bed. Grab-samples are not considered a useful alternative because they would also show bias since the sand has a heterogeneous distribution along the bed. Longer sampling times, over a greater range of flows, would improve sampling accuracy. With the relatively small amount of sediment caught in the nets, a large pebble caught in the time frame allotted could significantly skew transport rates toward greater transport than is actually occurring. Channel bathymetry was measured in the field (for a certain flow) and estimated for bankfull. The model assumes a rectangular cross section. A rectangular cross section would result in greater transport rates, since flow rates at the thalweg would be the same across the channel. In reality, rates are much less near the banks, where depths and velocities are much lower. However, the higher transport rates based on the model are consistent with this rationale.

Return periods associated with high rates of movement, based on data from the gravel bars input into the model, were relatively low. The longest return period for the highest rates of flow (and greatest depths) was just under 1.5 years. The frequency of relatively high flow events (compared to average flow) is associated with the flashy flow regime common to this region. It is not only the extremely large, infrequent events that mobilize sediment on the bars and in the channel, but also the moderate, more common events.

Further study of bedload transport, especially covering entire cross sections at several locations along the river, as well as measurements made at higher flows, would prove valuable in assessing detailed modifications in the morphology of the channel stemming from mining activity. While this study focused on the transport of bedload gravels, measurement of transport rates of the sand-size fraction of sediment in the channel would provide additional data about the actual movement of fines upstream, and downstream of mining sites. Models of such transport prove useful in estimating how the system reacts to change. Calculations can be compared to measured data to help determine what other factors control morphometric processes acting in the channel. With further evaluation, estimates can be made about how a river will accommodate changes brought on by mining, and hopefully reasonable guidelines can be set to establish necessary (but not excessive) buffers, vegetation, and other strategies to prevent breaches between gravel pits and the main channel.

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VITA

Cody Michelle Simmang was born to Cynthia Janet and Orville William Simmang Jr. in San Antonio, Texas on July 10, 1977. After graduating from James Madison High School in 1995, she attended The University of Texas at Austin and earned her Bachelor of Science in Geology in 1999. She worked at the United States Geological Survey as a hydrologic technician and at Core Laboratories as a geologist before returning to Texas State University-San Marcos to complete her Master of Science in Geography, with a focus on fluvial processes. While in school, she was an instructional assistant for the geology program, and taught labs for physical geology, historical geology, and mineralogy.

Permanent Address: 4701 Monterey Oaks Blvd Apt 1415

Austin, TX 78759

This thesis was typed by Cody Michelle Simmang.