DETERMINING MINIMUM RECREATIONAL INSTREAM FLOW REQUIREMENTS FOR A REACH OF THE BRAZOS RIVER AT GLEN ROSE, TEXAS

By

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Introduction

The purpose of this research is to assess the in stream flow conditions of the Brazos River near Glen Rose, Texas from the perspective of determining flow levels sufficient to maintain the integrity of the river channel as a recreational and ecological resource. The study is deemed necessary in light of the application by the Brazos River Authority (BRA) to the Texas Commission on Environmental Quality (TCEQ) for allocation of an additional one million acre-feet of available Brazos River flow, to be used by BRA for current and future needs, based on predictions of population growth for the next two decades. As a result of the June 2004 application, and in light of current flow conditions in the Brazos, an effort to block the permit was launched by a group of concerned landowners and river advocates.

The Friends of the Brazos River (FBR), a grass roots organization of local landowners and river enthusiasts, spearheaded by landowner/ river advocate Ed Lowe, and the Brazos River Conservation Coalition, a group of concerned businessmen and women, have launched an effort to prevent granting the BRA further unfettered claim to the dwindling resources of the Brazos. Compounding the concerns of the two groups is the somewhat circuitous route taken by the BRA request and the finality with which such a permit will hand over control of the remaining Brazos flow, effectively granting total rights to the authority to confiscate, allocate and disperse with great flexibility every cubic foot of this stressed *public* waterway.

At the center of the conservationists' efforts is the contention that current commercial uses, including gravel mining operations and nuclear power generation, have so compromised the health of the Brazos fluvial and riparian ecosystems that it is untenable to suggest that further tampering with the flow would be without associated increases in deleterious effects. Of particular concern to the river groups is the deterioration in channel openness and riparian zones that has noticeably occurred in the past two decades. A lack of intensive study of the current status of the river by the TCEQ and state water development board has raised the level of outcry by those opposed to granting further "operational flexibility" to the Brazos board (Parker, 2005).

As presented to the TCEQ, the BRA application had not only circumvented administrative procedure, but also failed to carry out an environmental assessment of the current Brazos status and the predicted impact of future water allocations – that is, flow level reductions and accompanying stress to riparian zones, deterioration of water quality during drought stages and accompanying stress to aquatic life, and increases in sedimentation due to reduced stream power and associated changes in the channel capacity to support recreational use. The aim of the permit's opponents is to prevent issuance of the BRA's request prior to a comprehensive environmental assessment and review of a water management plan by the BRA. It is imperative that the health of both the channel and riparian areas be thoroughly assessed and current flow conditions examined so that minimum flow requirements can be established before further development or impoundments are allowed in the basin.

Objectives

The objectives of this study are twofold: (1) determine minimum in stream flows for recreational purposes, specifically kayaking and canoeing, in the reach of the Brazos River between Lakes Granbury and Whitney; and (2) provide a baseline survey of channel bars and deposits at two important sections for further long-term monitoring of channel change and bar dynamics.

Literature Review

Human impact on flow regimes

The complexity of the relationship between flow regime and fluvial morphology makes precise determination of responses to impoundment difficult due to the difficulty attributing current ecological and fluvial conditions to a single specific episode of regulation or alteration. Further complicating the Brazos hydrogeomorphic regime is the combination of impoundment, flood control and hydropower structures currently operating in the basin. The multitude and magnitude of water use allocations make it imperative that the approach to basin-wide management be geared toward integrated strategies of conservation and remediation in order that economic, ecologic and municipal needs be met in concert with maintenance of healthy riverine systems. The spatial and temporal variability of river systems as networks of interconnected processes make evaluation of these systems extremely complex and the results of such studies imprecise. As a dynamic and highly variable system evolves and adjusts to disturbances it becomes increasingly less likely that any one management strategy can be effectively used to maintain a healthy riverine system.

Currently, the state of Texas has regulatory and market-based strategies for determining target environmental flows, neither of which is prioritized toward determining, much less providing, optimal environmental flow requirements. It is recognized and mandated that the waters of Texas are to be held in trust for the people of Texas, while not granting the TCEQ the authority to allocate water dedicated to the environmental health of the rivers comprising Texas' surface water supplies (SAC, 2004). Research by Poff and Allen (1997) into degradation of river systems by anthropogenic uses concluded that the most culpable factor was the reduction in magnitude and frequency of maximum and minimum flow stages caused by impoundment and the resulting disruption of the natural hydrologic cycle (Poff and Allen, 1997).

Magilligan's (2001) research on post-impoundment reduction in flow used pre-dam flow regimes to compare magnitude of low and high flows, based on prior proposals by Wolman and Miller (1960) that the two year flood was the dominant discharge for efficient removal of sediment and maintenance of natural channel morphology. The work of Andrews (1980) also supports the notion that post-dam diminished flows are not sufficient to remove sediments and debris deposited in the channel by tributaries, thus increasing growth of bars and vegetation, and resulting in decreasing channel cross-sectional areas. Floodplain sediment deposition and storage are major factors in maintaining channel openness, and must therefore be considered when determining optimal flow levels.

Earlier work by Jacobsen (1995) proposed that the greatest fluctuations in sediment storage occur at and near confluences, and that morphological heterogeneity as well as habitat creation are typically greater at confluences where fluctuations in sediment supply and the ability of the stream to remove deposits are the prime controls on channel geometry (Benda et al, 2003). The Benda study also points out that the episodic nature of sediment supply and movement is based on stream discharge levels and disturbances in the form of floods, fires and storms, particularly the magnitude and frequency of such natural processes.

Flow levels necessary to maintain channel openness are interrupted by flood control and reservoir storage structures which prevent the naturally occurring high and low flow levels necessary for sediment transport. Based on studies of morphologic effects at tributary junctions due to abrupt increases and decreases in flow, Benda et al. (2003) hypothesized that effectiveness of sediment and debris removal from channels, particularly at confluences, is determined by stream power. The three main sediment transport processes are determined to be debris flow, normal run-off and flash floods (Bull, 2002). Stage and frequency reduction by dams was estimated to be 60% after impoundment (Magilligan and Nislow, 2001), and believed to result in a major impact on channel characteristics, which are largely determined by the timing, magnitude and frequency of flood events (Magilligan and Nislow, 2001). Leopold determined that the two year recurrence interval flood level was equal to bank-full stage in natural rivers, and that the capacity of the river to transport sediment and debris is greatest at bank-full stage (Wolman and Miller, 1960; Andrews, 1986; Carling, 1988). Magilligan and Nislow's (2001) analysis also indicates a 90% reduction in frequency of the 2- year flood after impoundment.

Poff and Allen's (1997) studies of river restoration and conservation emphasize the importance of incorporating into watershed management regimes those practices that allow the dynamic nature of river systems to control the processes that determine morphologic and ecologic features within that system (Poff and Allen, 1997). He maintains that the integrity of rivers depends on their natural dynamic character, a fact typically not addressed in common watershed management decisions, and further stresses the importance of flow levels and timing related to water availability, water quality, and riparian ecology (Poff and Allen, 1997). A dynamic river system remains in a constant state of flux, adjusting to disturbances in flow in an effort to maintain a balance between discharge and channel morphology. equilibrium, and resulting in characteristic morphologic and ecologic responses. In light of the complexity and quantity of simultaneously occurring processes, and spatial and temporal variability of flow, it is impossible to artificially re-create the fluvial responses that can restore natural conditions to an altered or regulated watershed. Historically, the result of impoundment and flood control has been a smoothing of the hydrologic curve due to elevation of low flow stages and lowering of high flood stages, resulting from flow regulation. Diminished frequency and magnitude of flood events result in an increase in sediment supply deposited by tributaries, as the main channel at low water levels does not have the capacity to remove large deposits from tributary mouths. A decrease in magnitude and frequency of large flood events prevents the clearing of bars and islands that would naturally occur only with a flood event of 25, 50 or 100-year recurrence interval or greater.

Groffman et al. (2003) published a review of the necessity of analyzing the effects of urbanization on riverine ecology and determined that the impacts of excessive urbanization over time create a “hydrologic drought” for riparian areas deprived of natural hydrologic processes and controls as rivers become channeled and regulated. Lower water levels have implications on characteristics of rivers ranging form narrowing of channels, invasion of non-native species due to infrequency of flood events necessary to destroy preferred habitat, deteriorating water quality due to high salinity and pollutant levels that increase as the river’s ability to dilute non-point source pollution decreases. Scouring of channel bed and banks by sediment-starved water released from reservoirs, alteration of natural channel form as an attempt to re-establish equilibrium after disturbances, the inability to filter large amounts of urban channelized run-off and released water during storm events, also contribute heavily to deteriorating overall water quality.

The resulting changes in channel characteristics occur as a natural response by the river system in an attempt to maintain a state of dynamic equilibrium between discharge and sediment load, and with increased impacts from regulation the character of the river changes: channel slope, depth, width, and sinuosity and amount and composition of bed material can be significantly altered. The river may maintain this new state of equilibrium until occurrence of an extreme storm event (50-100 yr. recurrence interval) and over bank flooding and higher discharge rates remove large amounts of accumulated sediment and debris. The channel may become less sinuous as a result of greater stream power causing meandering loops to be cut off by the river breaking through existing banks. Although eventually the system returns to a state of dynamic equilibrium, a dynamic balance between channel morphology and fluvial processes (Ritter and Miller, 2002), the occurrence of such an extreme event represents the cycle of a dynamic river system on a much larger scale than does the typical controlled or regulated river system. Natural river network dynamics respond to changes in discharge levels with shifts in channel morphology and associated fluxes in sediment accumulation.

Human Impact on Sediment Transport

Water resources investigations on the Lower Brazos watershed were conducted by the USGS to determine the factors affecting sand transport in the channel, including the impact of 1178 reservoirs listed in the 1986 TNRCC dam inventory of the Brazos Basin (Wurbs et al., 1988). The report cites a coastal erosion study of Matheson and Minter (1976) who determined that diminished sand transport caused by trapping of sediments in reservoirs is the cause of the entire amount of sand lost in the coastal zone since 1937 (USGS, 2001). A 1973 study by Seely and Sorenson further supports theses findings, that beach erosion in the Gulf Coast is exacerbated by the decrease in inputs of sediment from the Brazos drainage basin caused by the construction of reservoirs.

Benda et al. (2004) identified three principle processes governing the efficiency with which sediments and debris are transported through a river system, thereby determining and modifying channel morphology, and their implications on a broader scale of river networks, primarily physical characteristics and ecological implications. Benda's focus was on the morphological impacts created at tributary confluences by decreases in stream power. Benda's work departs from the theories accepted in the last twenty years of a riverine system as a continuous linear concept, and instead adopts an approach that identifies the discontinuous properties of fluvial processes as they create a heterogeneous network on a basin-wide scale. The dynamic network view of rivers presents the characteristics of the river network as a constantly changing system striving toward equilibrium. The response of a river to disturbances from flood, storms and fires results in a continually adjusting channel and floodplain morphology and an equilibrium state of fluctuation.

The 2001 USGS report examined the link between reservoir construction on the Brazos and the capacity of the river to transport sediment (USGS, 2001). The investigation was aimed at analyzing the causes of increased coastal erosion in the Texas Gulf of Mexico, but their findings can be generalized to apply to the broader issue of impacts on channel morphology along the entirety of the Brazos watershed. They determined that increased bar formation in the channel was the result of lower magnitude of peak discharges, and that overall the transport of sand-size particles had diminished since the construction of numerous reservoirs. The complexity of interactions between processes of the hydrologic regime had not been unraveled to the point that any one factor could be positively identified as the cause of the decreased load. The USGS study took into consideration such factors as sediment trapping in reservoirs, climatic influences, particularly the extended drought that affected the basin in the 1950s, and changes in agricultural practices in the basin. The study proposed that a reduction in sediment transport might stem from a change in agricultural practices in the basin since 1924, when the main crops of cotton, corn and sorghum began to be replaced by hay, a crop much less likely to contribute to large amounts of soil erosion.

Magilligan et al. (2003) proposed that channel restoration could not be accomplished with a single flow or discharge, due to the complexity of riverine habitats and the enigma of establishing pre-impoundment conditions. It is reasonable to conclude that there is no one minimum flow level that characterizes the flow regime for a river system, but that the ideal flow level is constantly adjusting to natural spatial and temporal perturbations along a channel in order to maintain a balance between sediment transport and discharge. The findings of Dunne and Leopold (1978) that "Human modification of natural hydrologic processes disrupts the dynamic equilibrium between the movement of water and the movement of sediment that exists in free-flowing rivers" have been followed by considerable research aimed at identifying equilibrium flow levels. Some results suggest that the true equilibrium discharge is the bank-full stage, as that level is responsible for development of bars and riffle pool sequences that move significant amounts of bed or bank sediment frequently enough to continually modify channel morphology (Poff and Allen, 1997). When determining minimum flow requirements, spatial and temporal variability within the system must be considered in order to arrive at flow levels that allow natural fluvial responses to provide long-term channel adjustment to disturbances.

A four-stage process for assessing the current condition of the Brazos has been proposed by the environmental consulting firm of Joseph Trungale (Austin), and is outlined in his recommendation for a comprehensive in stream flow study. Suggestions include a desktop analysis of river management models, a recreational flow levels study, an ecological flow study and a multi-year, multi-discipline in stream flow analysis. The recreational flow requirements segment will also include portions of the desktop analysis as is required to establish pre-dam stream flow levels and minimum levels required for recreational use and channel maintenance. Establishment of pre-impoundment levels is a crucial component of forecasting the effects of future flood control/reservoir construction, and determining healthy base flow levels.

A United States Department of Agriculture summary of research quantifying channel maintenance determined that channel maintenance in stream flows are designed to maintain those physical characteristics of the stream channel critical to unimpaired flow and sediment conveyance, and a stream channel in a fully functioning condition conveys water and sediment without aggradation or degradation, dissipates energy, reduces flood peaks, sustains flows, and otherwise acts as a natural stream (Schmidt and Potyondy, 2004).

Site Description and Climate

The Brazos River Basin originates in eastern New Mexico and encompasses an area of approximately 45,000 square miles, extending to the Gulf Coast at Galveston, TX. (Fig.1). The watershed has been sub-divided into three segments - the North Brazos Basin, Central Basin, and Lower Basin. The largest of the Brazos reservoirs, Lake Whitney, is located in the Central Basin. From the days of earliest American settlement in the early nineteenth century, the economic value of the Brazos River was top priority in the minds of those who viewed it as an economic asset and source of transportation for the goods produced in the interior reaches of the river basin. The dynamics of the Brazos watershed made shipping all but impossible, and early in the century the men who saw the towns at the mouth of the river as vital economic centers decided that any and all obstacles to navigation must go – including (courtesy of mother nature) sandbars, snags, sunken trees and shoals – in order that a navigable open shipping channel be maintained.

> "The vagaries and extremes of the (Brazos) river's behavior are so great that men soon realized she must be tamed and controlled if they were to prosper..."
>
> (Hendrickson, 1981).

Throughout the early days of settlement the farmers along the Brazos floodplains were at the mercy of climatic cycles that brought devastating floods, followed by crop scorching droughts. They watched helplessly as

Fig.1 The Brazos River Basin (12) originates in New Mexico and encompasses ~ 45,000 square miles, extending to the Gulf Coast at Galveston, TX.

raging floods gobbled up tons of worn out topsoil from their fields, and deposited thick layers of sand over formerly fertile farmland.

Although the Brazos River Conservation and Reclamation District, currently the Brazos River Authority, was established in 1929, it wasn't until 1941, after years of political and financial wrangling that the first dam, at Possum Kingdom went on line to produce hydroelectric power and control flooding. Bedrock composition beneath the lake was very high in chlorides and created problems thereafter with salinity levels in the river (Hendrickson, 1981). Throughout the mid twentieth century economic growth in the basin continued to strain the ability of the river to meet irrigation and municipal water demands using surface water alone. The mindset of the members of the river board at the time was that any water not harnessed for power or stored in reservoirs was wasted water: "...an average of six million acre-feet of water flowed through the Brazos each year, but most ...was wasted into the Gulf of Mexico. Particularly at its peak stage the river was a water waster." (Hendrickson, 1981). It was this rationale that became the justification for the chain of dams to be built along the Brazos between Possum Kingdom and Whitney. The reigning belief in the late 1950's, as editorialized by the Waco Times Herald, was that through impoundment and flood control the "complete management of the river and its tributaries (would be) made possible. "(Hendrickson, 1981).

The Brazos River watershed drains an area of central Texas between eastern New Mexico and the Gulf of Mexico south of Houston. The river is a 640-mile long meandering channel incised in bottomland sands, with an average slope of 0.7 $ft.mi^{-1}$ (USGS, 2001). The study area is the reach of the Brazos River in Glen Rose, Texas between the FM 200 Bridge (USGS gauging station 080910000) and the confluence of the Paluxy and Brazos Rivers with Squaw Creek. It is located within a 110 km reach of the river between Lakes Granbury and Whitney, considered the middle Brazos River basin (Fig. 2), an area of central Texas marked by gently rolling hills and cattle ranches. This area of the Texas prairie region has a sub-tropical sub-humid climate, with hot summers and dry winters, and is currently experiencing severe drought conditions marked by alarmingly low surface water levels. The study will include mapping of the river and tributary junction, as well as determination of critical sites at which to measure cross-sectional channel capacity. The reach is located ~60 miles southwest of Fort Worth, at which point the Brazos runs through Hood and Somerville Counties to Lake Whitney in Bosque County. Soils are heavy textured clays and sands, suited for rangeland and general agricultural uses. According to a Texas Parks and Wildlife publication of an analysis of Texas rivers, recreational use of the area of the Brazos River between DeCordova Bend dam (downstream of Lake Granbury) and Lake Whitney is not possible without release of water from the DeCordova Bend dam (Texas Dept of Parks and Wildlife, 1974).

The study area is located at the confluence of the Brazos River, Paluxy River and Squaw Creek (Tres Rios) and represents a critical area of channel geometry due to the complexities of dynamic river processes that occur at tributary junctions (Fig. 3). Tributaries represent abrupt increases in the supply of water, sediment and wood debris; therefore, channel responses related to such disturbances should be of higher frequency and magnitude near or immediately downstream of confluences (Benda et al., 2004). Earlier work by Jacobsen (1995) proposed that the greatest fluctuations in sediment storage occur at and near confluences, and that morphological heterogeneity as well as habitat creation are typically greater at confluences where fluctuations in sediment supply and the ability of the stream to remove deposits are the prime controls on channel geometry (Benda et al, 2003).

Daily discharge data from USGS gauging station (No. 08091000), located approximately one mile upstream (east) of Tres Rios, was analyzed to quantify the flow regime of the Brazos downstream of Lake Granbury, including frequency and duration of flow, timing of high and low pulses, and rate of change in conditions. The complexity of and connectivity between fluvial processes make it difficult to identify the specific disturbance or event responsible for a specific channel response. Critical channel characteristics will reflect the impact of impoundment differently and thus need to be considered separately when devising an overall management strategy.

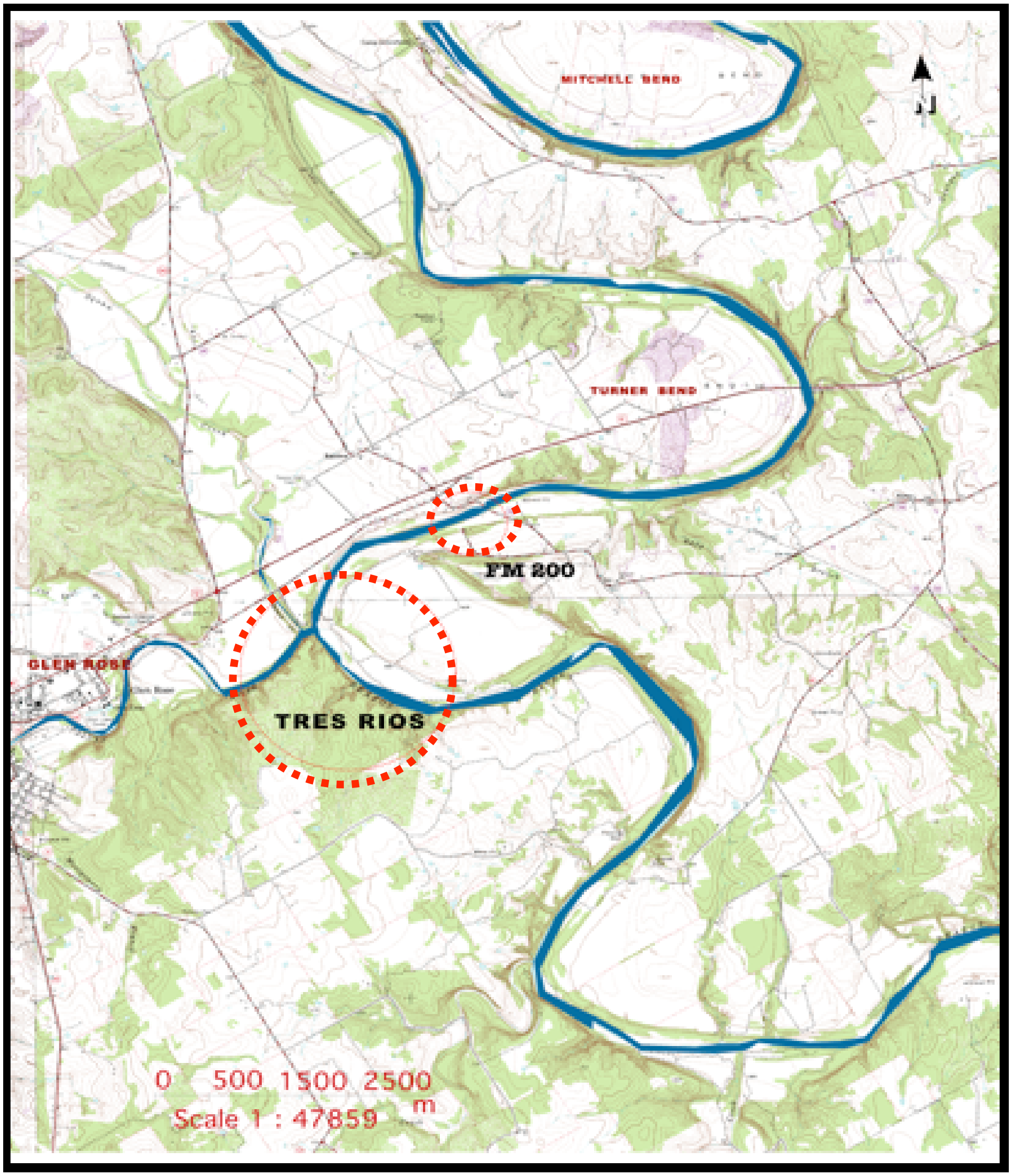


Fig. 2 Map of field area near Glen Rose, TX. Large highlighted area is the confluence of the Brazos River, Paluxy River and Squaw Creek, Tres Rios; smaller highlighted area represents the study reach in the location of the USGS gauging station No, 08091000 at the FM 200 Bridge.

USGS historic records from the Glen Rose gauging station were used to determine average discharge levels before impoundment as well as to assess the magnitude and frequency of disturbances. USGS records from the Glen Rose gauging station were also used as a baseline for data collected at the site, in order to correlate low, medium and high stage pre- and post-dam measurements. Comparison of pre- and post-impoundment data aids in quantifying the impact of past impoundment and projecting deleterious impacts of future alterations to the flow regime. Digital aerial photographs (USGS) were examined to identify the areas of the reach that most reflect the dynamics of sediment transport and current channel characteristics. Channel plan form maps were then constructed at those points thought to be most representative of adjustments in fluvial processes. Channel cross-sections and three dimensional digital terrain models were constructed to represent channel characteristics at high, low and bank-full stages. Historic aerial images were used to compare channel morphology before and after the closing of the Lake Granbury dam. This information can then be used to estimate the effects on flow level and critical areas of the channel of future withdrawals particularly the pending BRA request. Channel bars were mapped for the reach that begins at the FM 200 Bridge in Glen Rose to the confluence of the Paluxy River, Squaw Creek and Brazos River, and channel cross-sections constructed within that area.

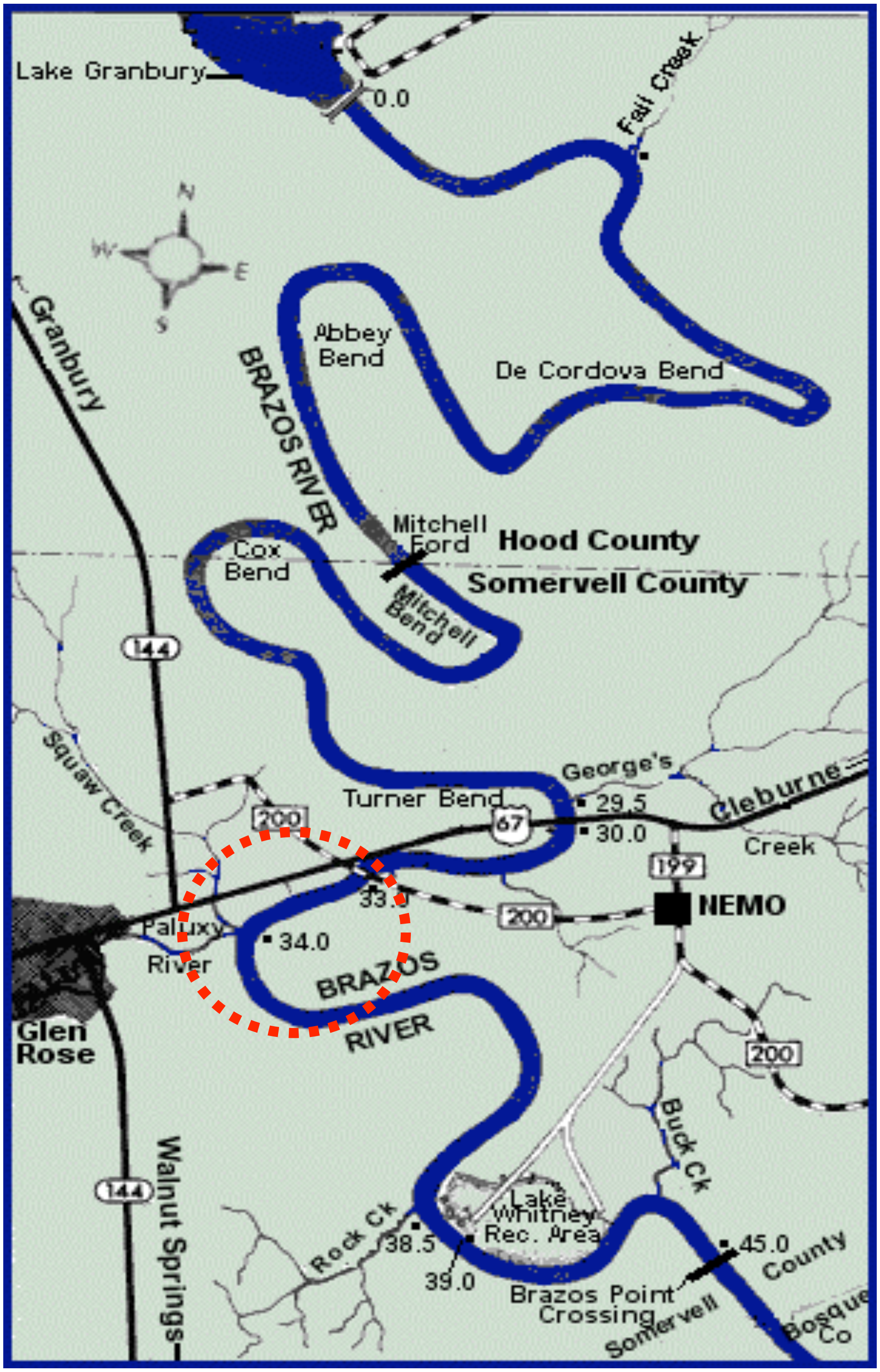


Fig. 3 Study area at the Paluxy River, Brazos River, Squaw Creek confluence in Glen Rose. TX.

Instream surveys were conducted, using a *Leica Total Station* digital surveying system and used to produce base maps for the study area at the confluence of the Paluxy and Brazos rivers with Squaw Creek (Tres Rios) and for the area beginning at the FM 200 Bridge and extending approximately 2500 feet downstream. The FM 200 bridge reach was mapped at very low water levels (*c.* 27cfs), or 94% exceedance probability, while the Tres Rios reach was mapped at (657 cfs), 35% exceedance probability. The channel surveys were done in order to establish a baseline flow level for comparison of the extent of sediment exposed in the bars at fluctuating water levels. These data were then used to produce images depicting the condition of the channel and bar features associated with variations in flow.

Three-dimensional representations of the sand bars at Tres Rios and at the FM 200 site were constructed using the *Surfer 8* computer graphics program. The digital terrain model can then be used to produce images of the island at incremental increases in discharge and water level. The optimal recreational flow rate range can then be determined, based on daily discharge data taken from the USGS gauging station at the FM 200 bridge, and predictions can be made based on channel openness at measured discharge levels. USGS records were then used as the basis for a comparison of pre- and post-impoundment flow duration records and changes in channel morphology. Calculation of three-dimensional cross-sections for the FM 200 and Tres Rios island sand bars were used to calculate tons of sediment in storage in the channel. Extrapolating the data to a larger scale, though not devoid of problems, does allow an estimate to be made of the amount of sediment being accumulated and stored in channel depositional structures rather than transported through the system. Pre-dam and current aerial photographs of the site were used to compare current channel structures to pre dam morphology in order to identify the changes in channel plan form since the closing of the Lake Granbury dam.

Results and Discussion

The flow duration curve for the Brazos River at Glen Rose, TX was constructed from USGS records for peak daily discharge in order that a comparison could be made between flow regimes for the pre-dam period, 1923 to 1966, and the period from 1970 to 2005, after the Lake Granbury dam was closed. The lower (blue) curve measures flows $\leq$ 100 cfs 43% of the time during the post impoundment period, while the upper curve representing pre-impoundment flow, measures flows of $\leq$ 100 cfs only 18 % of the time, a twenty-five percent decrease in frequency.

The effect of smoothing a hydrograph is reflected in the upper end of the Brazos River curve in the extreme flood event probability range; the same dampening effect carries through the range of median flows to the low flow range. It would be expected after dam closure that the low flow ranges would be higher for a larger portion of time, but in this case only the lowest range flows exceed pre-dam conditions. Typically, one expects to see a flattening of the flow duration curve, reflecting the lowering of stages during extreme flood events and the raising of stages during seasonal or extreme dry periods. Although the smoothing trend in the flow duration curve would appear to be beneficial for flood control and drought mitigation, impoundment has the overall effect of lowering flows in that the duration and frequency of flows are diminished. The lowering of discharge levels during extreme flood events, however, impacts sediment transport less favorably, reducing the sediment transport capacity and cycles of normal channel flushing.

The slope of these curves appears typical of humid environments: flow is not flashy, and discharge remains elevated for extended periods. Median discharge for the pre-dam period is 394 cfs; post-dam period median discharge is 164 cfs, indicating that flow regulation has significantly altered the hydrologic regime of the middle Brazos. Pre- and post-impoundment curves are of similar form, but because regulation increases the lowest flows and lowers the highest flows, generally post-impoundment curves can be expected to lie above pre-impoundment curves. In the case of this reach of the Brazos, quite the opposite occurs. Only the very lowest flows are elevated, while high magnitude flows are unaffected (see Fig. 5). This may be the result of the extended drought that the Brazos Basin area is currently suffering. The wide area between the 0.5 and 0.8 probability range is thought to reflect large withdrawals from the Brazos River (Fig.4).

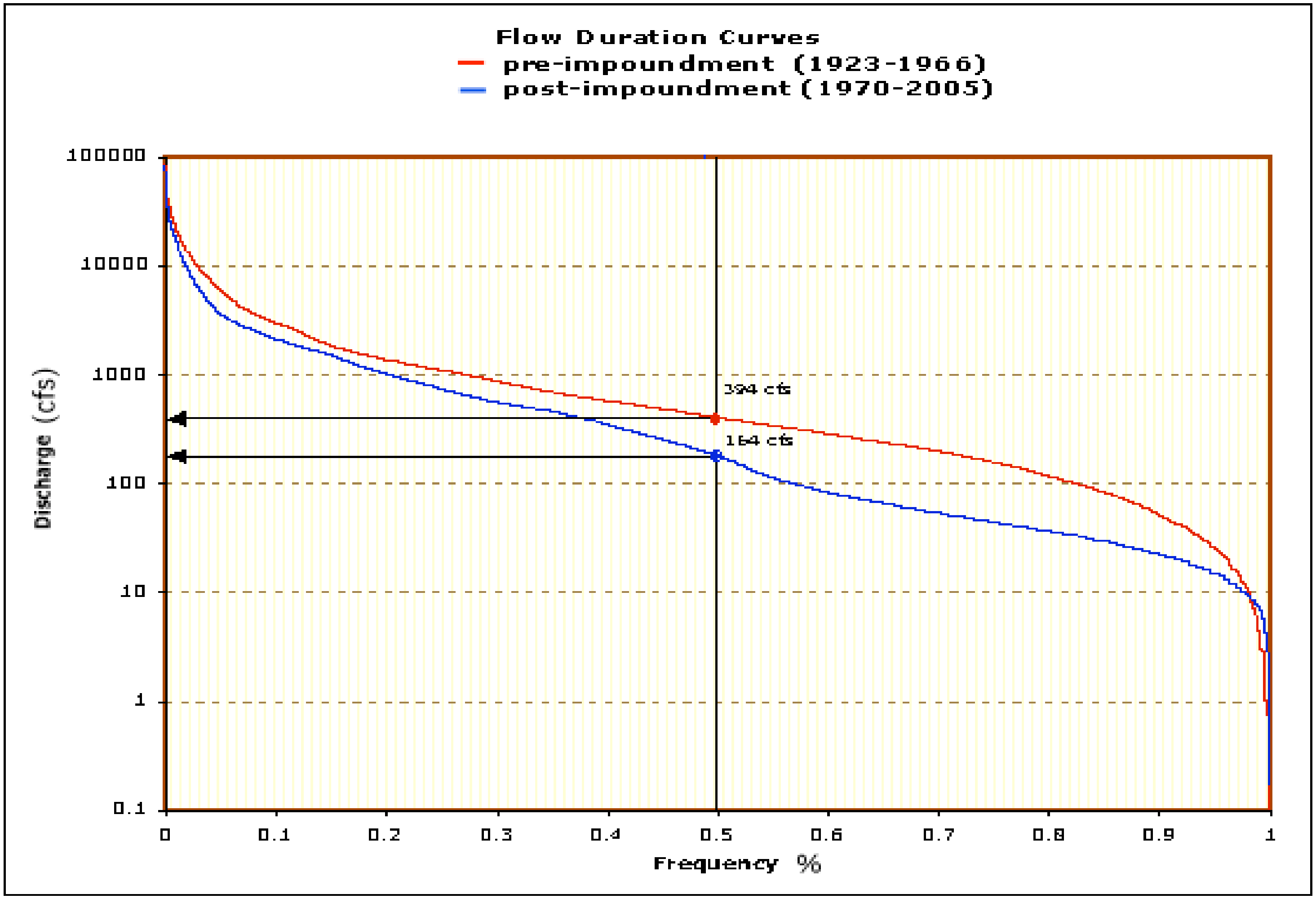


Fig. 4 Flow duration curve for the Brazos River, Glen Rose, Texas. Red line represents pre-impoundment flow; blue line represents post-impoundment flow.

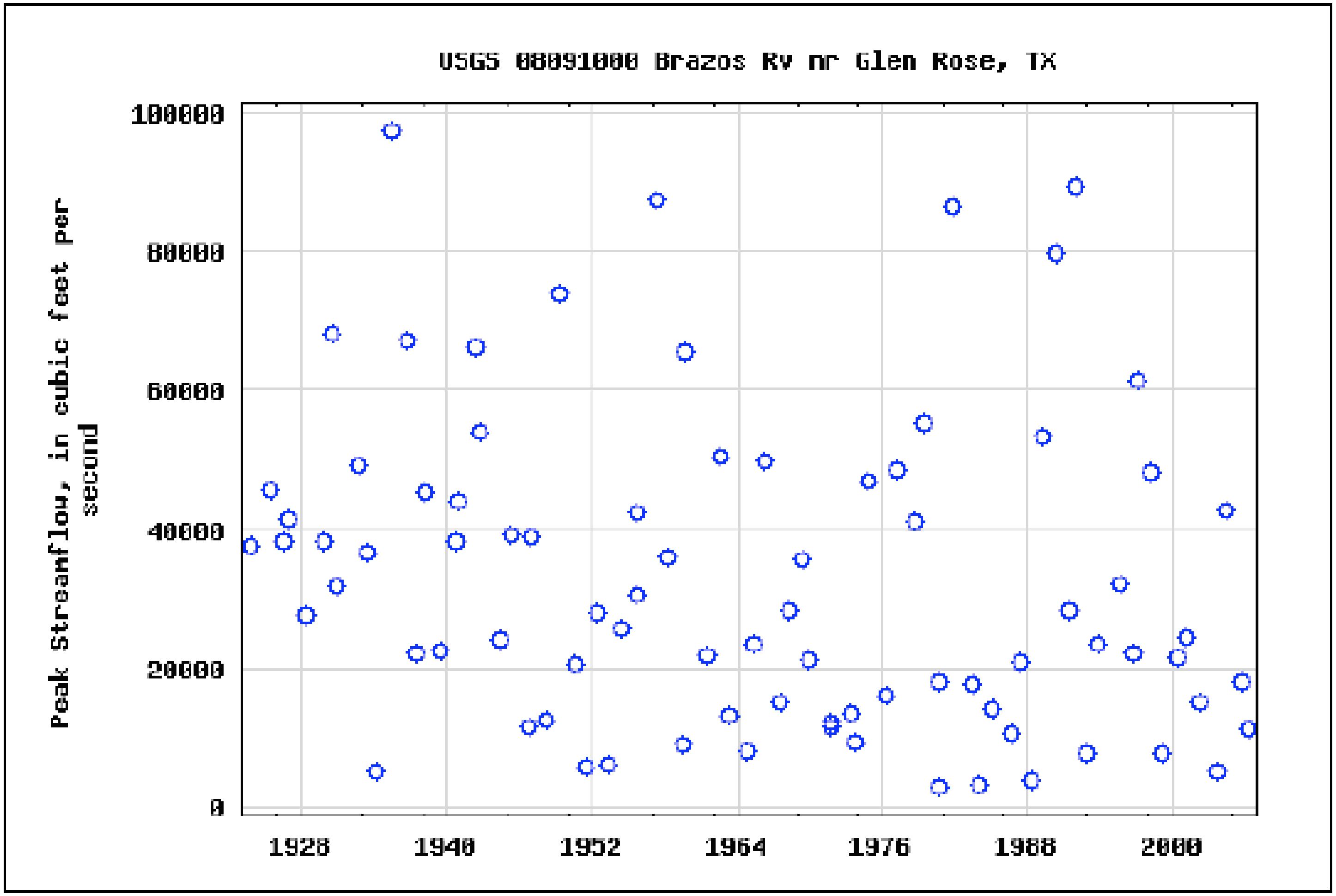


Fig. 5 Graph of maximum annual streamflow, Brazos River, Glen Rose, TX. (Dept. of the Interior, USGS Water Resources of Texas 2007).

Bridge (FM200) Reach

Three channel cross sections (Fig. 6), as well as the banks, bars and channel itself, were surveyed at the area of the reach extending approximately 2,200 feet downstream of the FM 200 bridge and gauging station. Flow level during the field survey corresponds to a USGS gauge height of 4.35 feet or 27 cubic feet per second, equivalent to a 94% flow frequency. This area is considered an important section of the reach because the channel here is shallow and wide and at low flow levels large expanses of sandbars are exposed, making the channel unnavigable in many areas. It is also an area from which many paddlers embark on their downstream journey toward Lake Whitney.

Cross section 1 (Fig. 7) was closest to the Tres Rios reach, approximately 0.5 miles downstream from the bridge, and shows a relatively confined, meandering channel, approximately two feet deep, and ~140 feet wide. At areas of channel narrowing, a discharge of 27 cfs does allow limited navigation along the scour pool adjacent to the east bank and shallows that are approximately 1 foot deep. Cross-section 2 (Fig. 8) is located approximately 500 feet upstream from section 1, and shows the channel becoming shallow and wider, to ~ 1.5 ft maximum depth and ~75 ft main channel width. Although some navigation is possible, pronounced

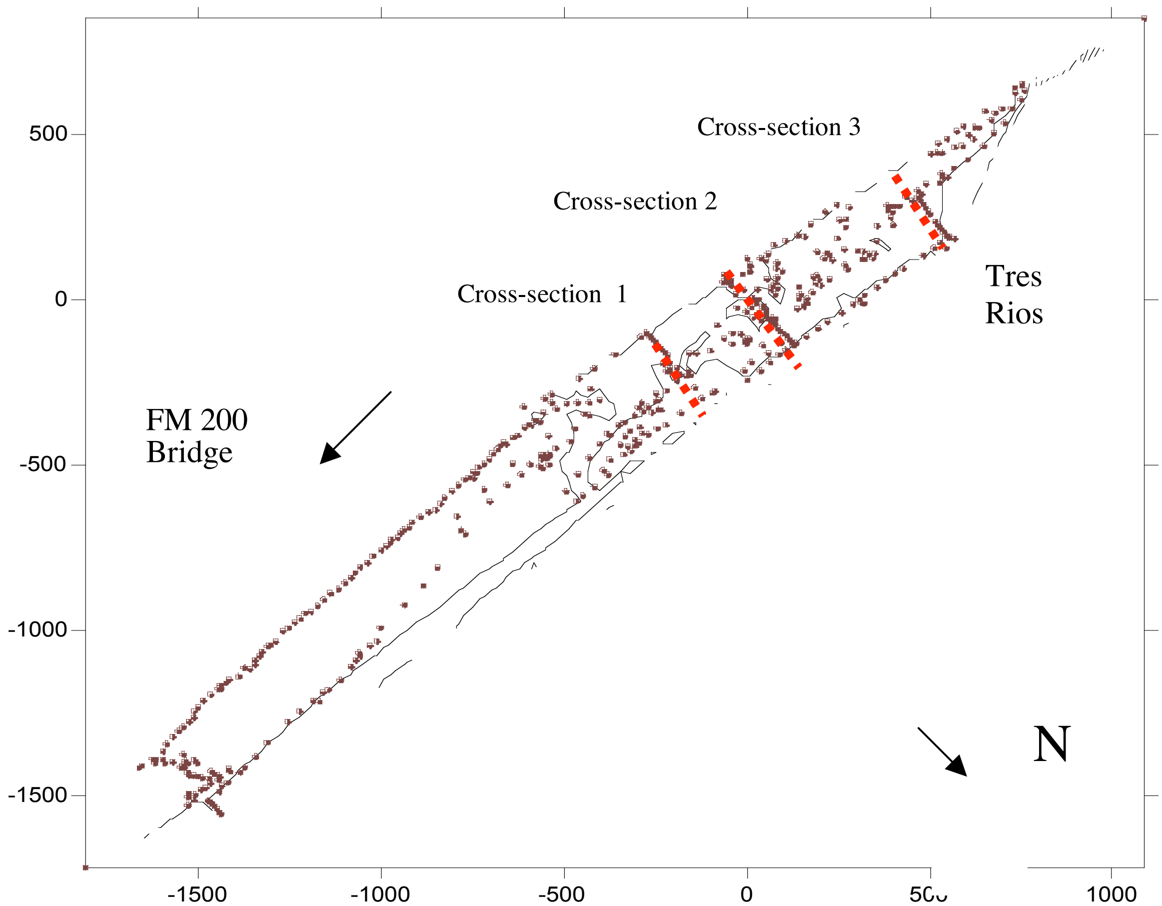


Fig. 6 Locations of three channel cross-sections surveyed at the FM 200 Bridge reach of the study site. (Red dots indicate cross-section locations).

bars are becoming visible. At cross- section 3 (Fig. 9), ~250 ft. upstream of cross-section 2, the channel has flattened dramatically to a maximum depth of ~ 0.5 ft., and a mean depth of ~. 129 ft., and shows typical shallow, wide low-flow channel morphology. At this depth the channel has large exposed longitudinal and lateral sandbars, and is completely unnavigable.

At gauge levels of 5 to 6 feet (145 to 520 cfs) water levels in the reach represented by cross-section 3, typically the reach with the largest exposures of gravel bars, would increase to a depth of ~ 1 foot, allowing navigation through most of the study reach. The wide range of morphologic characteristics typically comprising fluvial systems creates problems in precisely determining a one-size-fits-all flow range. Variations in channel slope, width, and depth along a river reach create a wide range of optimal flow levels.

Water levels taken from USGS data collected from the gauging station at the bridge (Fig. 10) show channel inundation, or the percentage of channel opening up with increasing discharge, the survey also allowed calculation of the amount of sediment stored in the channel bars. Sediment volumes in the bars were calculated using *Surfer 8* 3-D modeling software. Figures 11 a through j illustrate the effect of progressive increases in water level on channel inundation near the FM 200 Bridge.

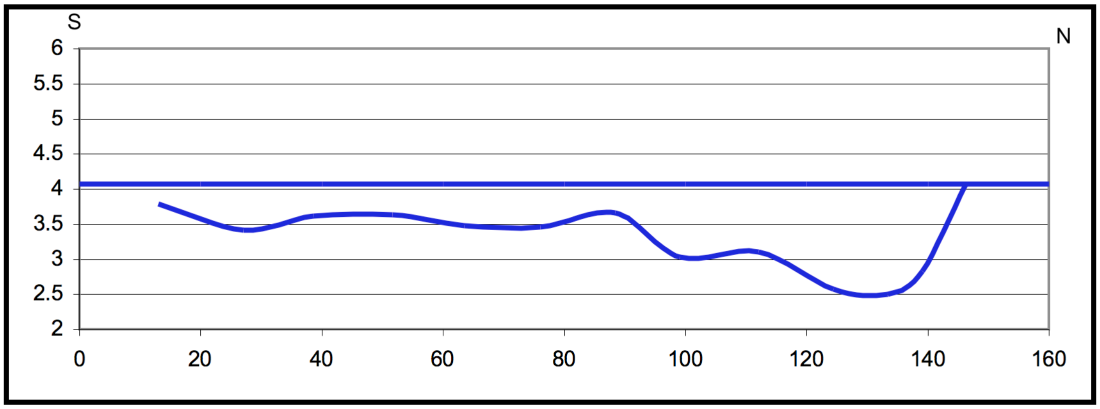


Fig. 7 Cross-section 1. ~. 5 miles downstream of FM 200 bridge, has flow depth ~ 2' and allows limited navigation. .

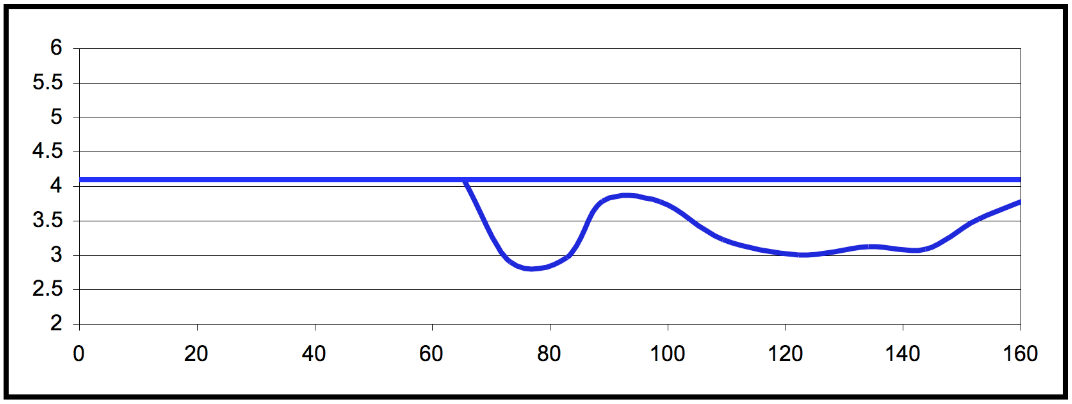


Fig. 8 Cross-section 2. Channel widens and shallows to ~ 1.5' maximum depth.

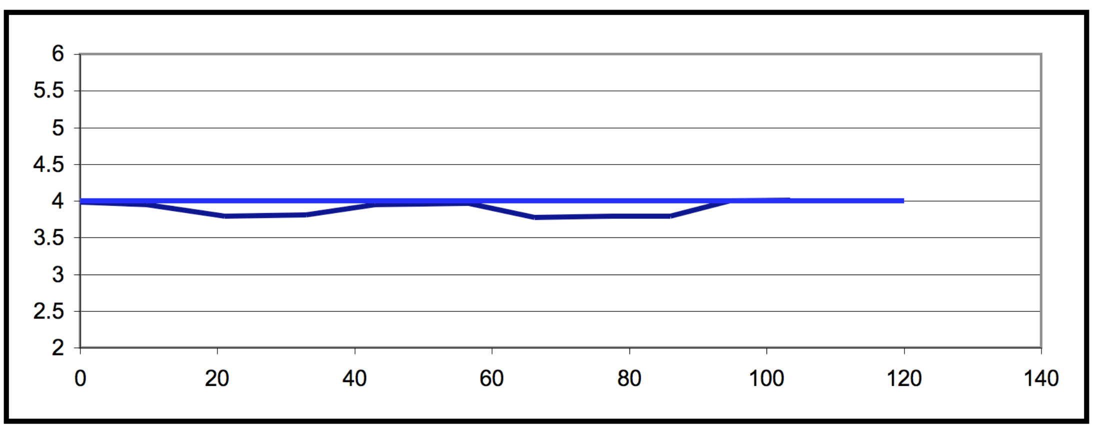
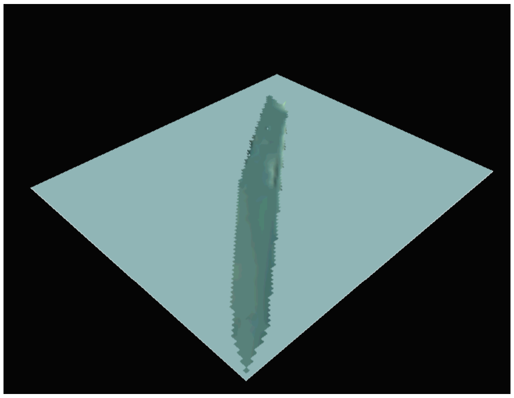


Fig. 9 Cross-section 3. Channel depth has decreased to ~0.5 ', and with large exposures of gravel bars, is unnavigable.

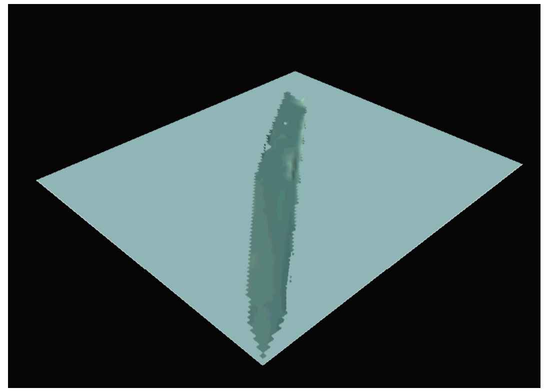
At a gauge height of 2.79 feet, equivalent to a discharge of 7.2 cfs, the volume of sediment exposed in the channel bar at the bridge site is more than six million cubic feet. Total volume of sediment includes that which is unsurveyed below the water line, but at discharge representing extremely low flows the calculation of the exposed sediment amount provides reasonable representation of the stored alluvium that stream power is working with at the onset of a storm event. At a gauge height of 4.35 feet (27 cfs) the channel bar in this reach was widely exposed and a water depth of ~1 – 2 feet constrained flow to a narrow channel with widely exposed sand and gravel surfaces. The flowing channel was too narrow to support normal maneuverability of recreational craft. Further reductions in stage from 3.8 feet to 2.8 feet leaves the channel proportionately unfit for recreational use.

Figure 12 shows daily stream flow statistics for the six-month period between May 1, 2006 and November 1, 2006 measuring gauge height and discharge, respectively. The elevated area of the stage and discharge record during the first 30 days represents what is normally a period of increased precipitation: levels drop significantly in the second month, the beginning of the summer which is normally a period of high temperature and low precipitation. The graph also records cyclic periods of high and low discharge representing planned water releases from the Granbury reservoir, which were provided by the river authority during the summer recreational period on a weekend-only basis. This policy is most likely related to pressure brought upon the BRA by the Friends of the Brazos to maintain reasonable water levels in the river. Thus water levels were between 5 – 6 feet gauge height on weekends, ~170 – 550 cfs, and dropped ~ 1 – 1.5 feet during the week to a low of ~4.05 feet gauge height, or ~7.2 cfs.

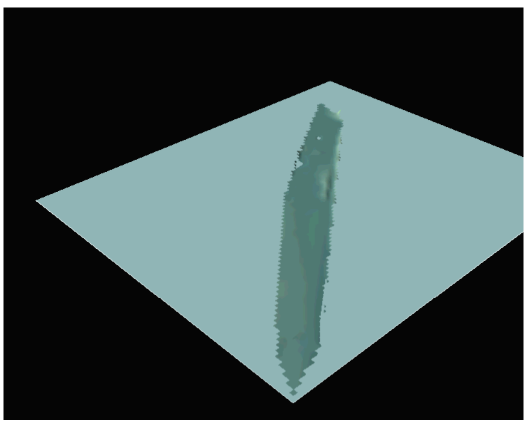
Fig. 10 View of sediment bars looking west(downstream) from FM 200 bridge.



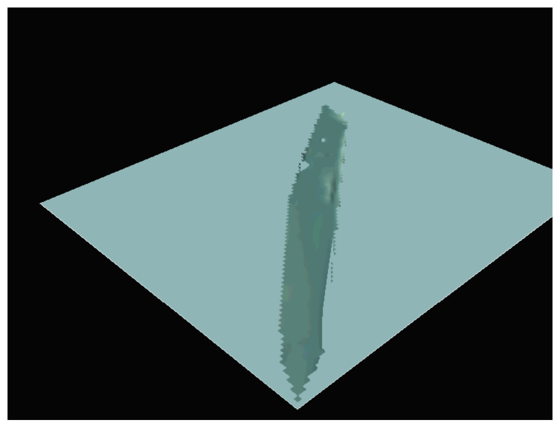
a) Vol. 272.6K T; Gauge 2.8’



b) Vol. 249.2K T; Gauge. 3.3’

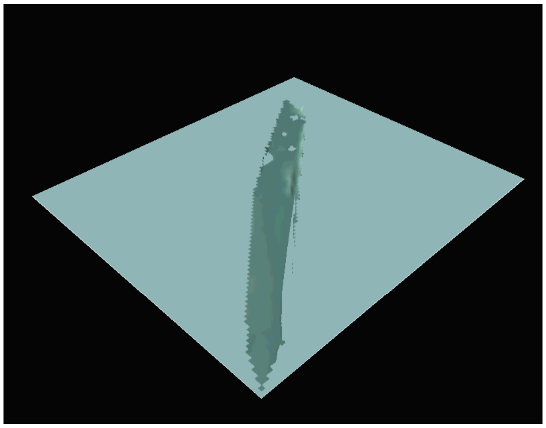


c) Vol. 226K T;Gauge 3.8’

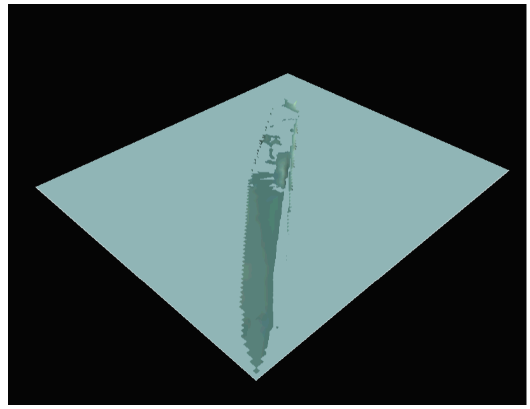


d) Vol. 203K T; Gauge 4.3’

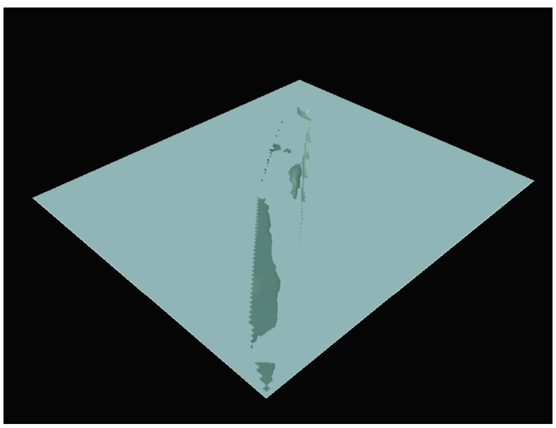
Fig. 11(a – j) Channel bar at FM 200 bridge reach of study area showing volumes of sediment at incremental increases in water level.



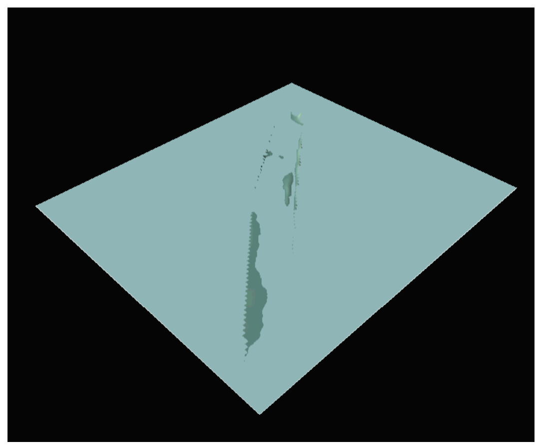
e) Vol. 181.2K T; Gauge 4.8’



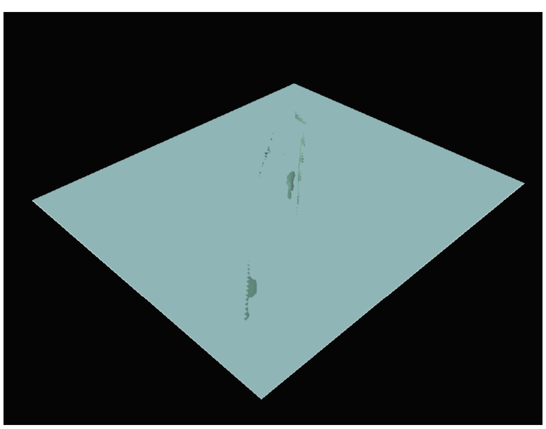
f) Vol. 162.0K T; Gauge 5.3’



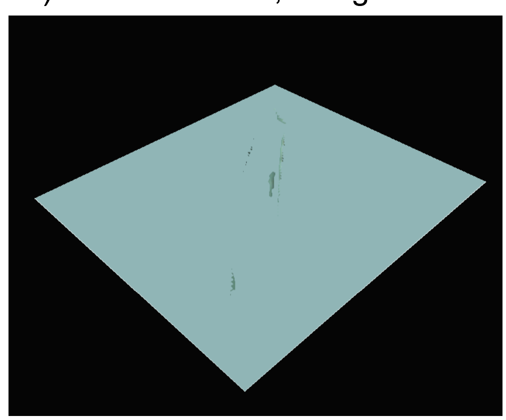
g) Vol. 151.0K T; Gauge 5.8’



h) Vol. 142.4K T; Gauge



i) Vol. 135.2K T; Gauge 7.3’



j) Vol 83.0K T; Gauge 7.8’

These gauge levels are in keeping with those found during the study to be navigable, namely ~6.3 ft. (650 cfs), the gauge height at the Tres Rios confluence during the channel survey, slightly higher than the peak weekend discharge during the planned releases. At a gauge level of ~ 4.35 feet (27cfs) measured mid-week, representing a time between water releases, this reach of the channel was unnavigable. Although the channel was considered navigable at a gauge height of ~6.3 ft., not all bar and riffle sequences were submerged sufficiently to provide clearance for watercraft. The 6.3 gauge height is more than the level attained from weekend releases, which reached a maximum of 5.8 ft, (300cfs) on only one weekend, and were typically 5.5 ft, (~200cfs) or less. USGS gauging station records (Figs.12 -13) illustrate those periods of discharge at or above minimal levels and those periods of insufficient flow related to seasonal drought conditions.

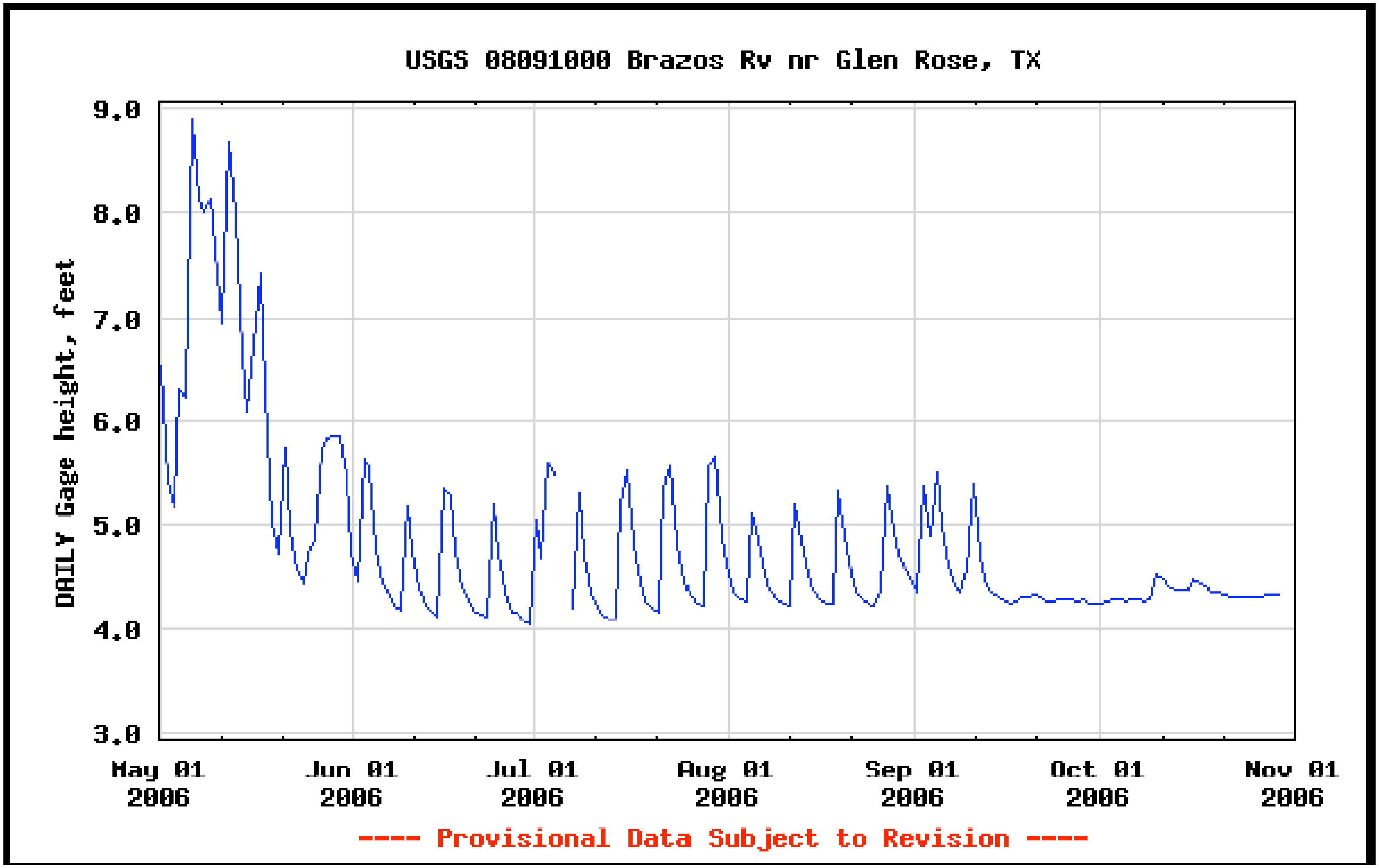


Fig.12 USGS graph depicting river stage during the period of planned weekend water realeases, (May, 2006 – Sept., 2006) for the Brazos River at Glen Rose, TX.

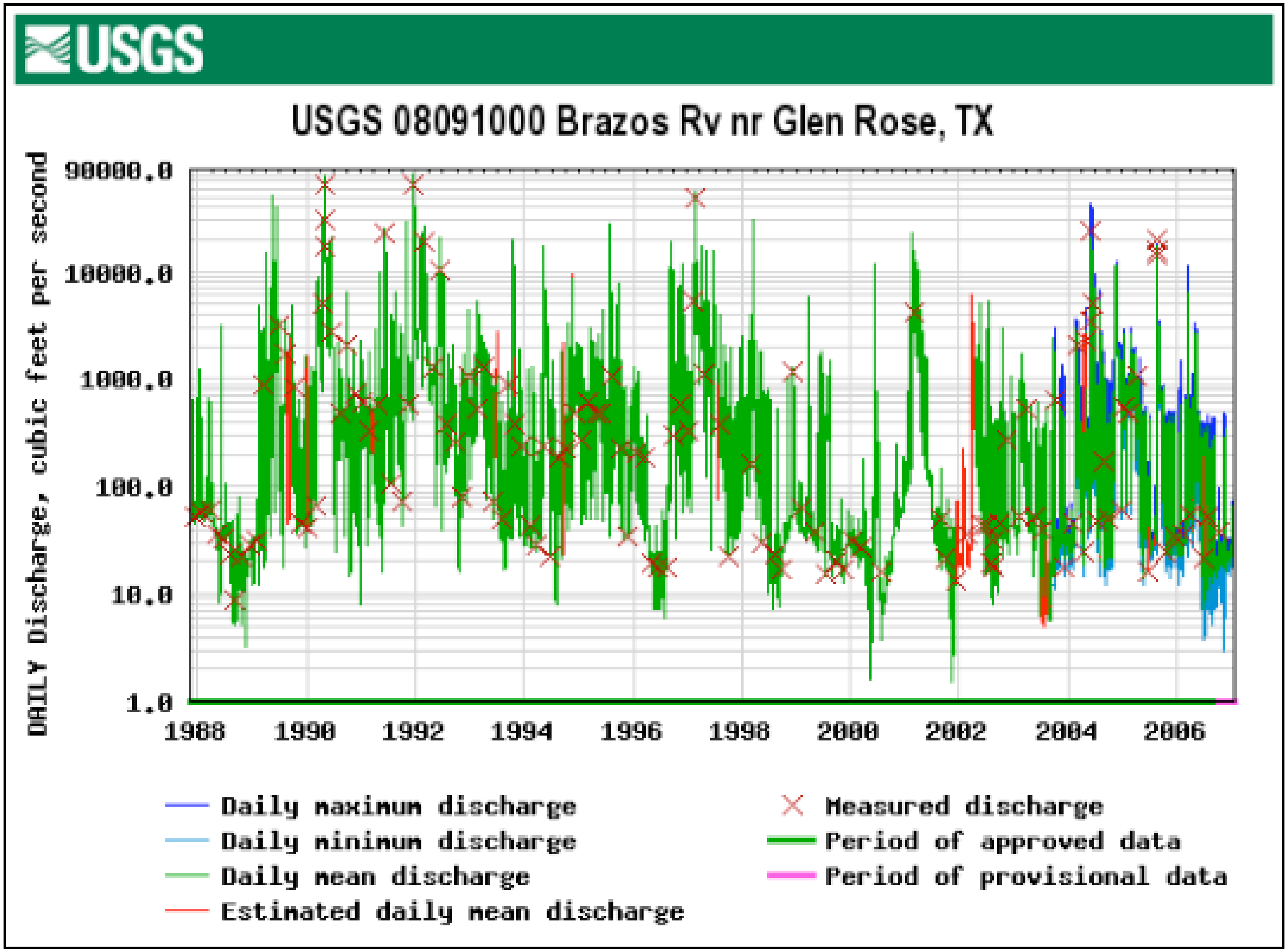


Fig. 13 USGS daily discharge records for the period Nov. 1987 – Jan. 2007

Tres Rios Reach

The second critical area of the study reach is shown in Figure 14. This section is at the confluence of the Paluxy and Brazos at the Tres Rios campground and resort. This is a very busy section of the river in terms of recreational use, but it is also an important area geomorphically. The Brazos makes a sharp left turn in plan-form at this junction and a large medial sand bar has developed in the main channel. The bar appears to also be fed by sediment transported by the Paluxy River as it enters the main channel of the Brazos. As tributaries enter larger river channels, difference in velocity between the two flow regimes, causes turbulence and mixing of sediments. The increased sediment load is deposited on the island bar as a result of decreased velocity in the Brazos. The decrease in velocity due to tributary input reduces the stream power of the Brazos main channel and impacts the efficiency with which sediment is entrained and transported. The resulting accumulation of sediments compounds the navigation problem over time as the bar becomes larger and more of an impedance to flow.

The obstructing bar in the main channel causes a deflection of downstream flow and initiates secondary flow on the channel floor, moving bed sediments toward the inner bank and deflecting flow toward the outer cut bank (Ritter et al., 2002). Over time the resulting change in channel geometry causes the system to respond by increased meandering and erosion of sand size sediment from cut banks. An increase in sinuosity causes a corresponding decrease in stream power and the flushing of sediments from the tributary junction. Decreased stream power causes additional response upstream of the junction as smaller sediments are deposited on longitudinal bars, as depicted in the highlighted area downstream of the FM 200 Bridge in the aerial photo.

Figures 15 (a – k) show the channel morphology at the Paluxy, Squaw Creek Brazos confluence at incremental discharge levels, illustrating channel openness for each river flow stage. Flow levels are correlated to USGS gauge heights for flow conditions on the survey date. At a gauge height of 6.3 ft. mean discharge is ~ 657 cfs, and the channel was open and navigable for recreational use, although the secondary channel at the northwest point of the channel bar did not have sufficient flow depth to prevent grounding of canoes on exposed bars and boulders (Fig. 14). This supports the conclusion that discharges below 657 cfs, though sufficient for navigation in many stretches of the river, would create channel conditions at critical areas that are less supportive of recreational use.

The peak discharge available during weekend water releases from Lake Granbury during the period from June to September 2006 was ~314 cfs or ~5.5 feet gauge height. It is therefore reasonable to suggest that discharge between 314 cfs and 650 cfs is the preferred minimum flow range for recreational use of the river, and that discharges below that level would create proportionate increases in volume of sediment exposed in channel bars, and a correlated decrease in channel depth, width and navigability.

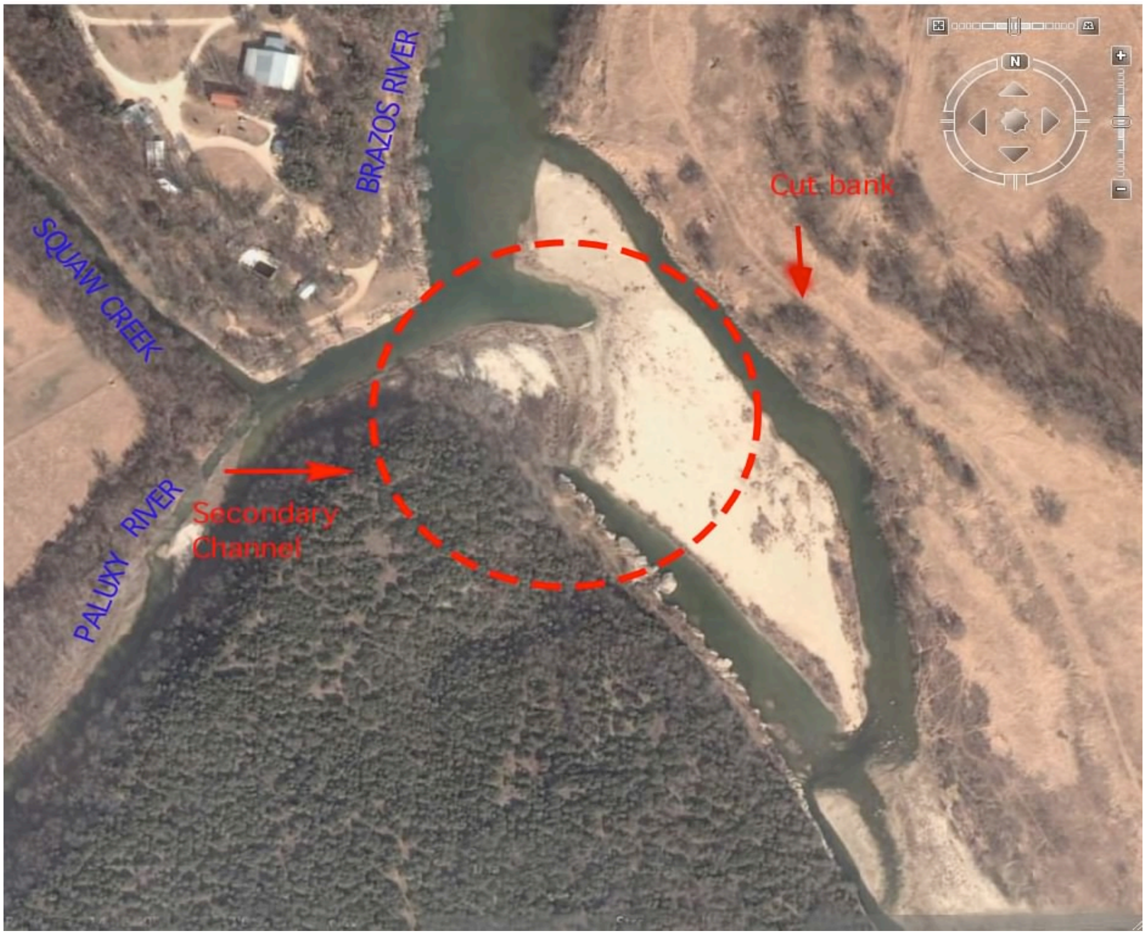
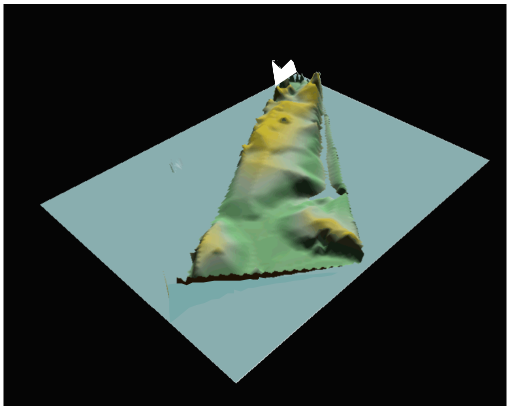
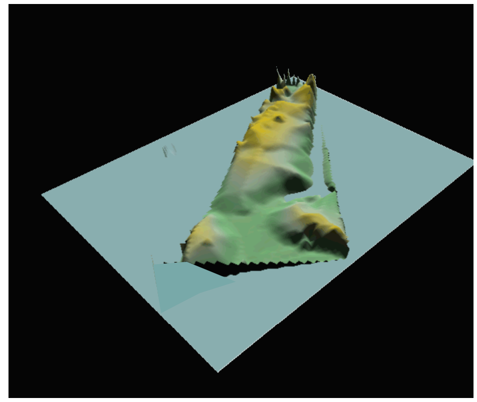


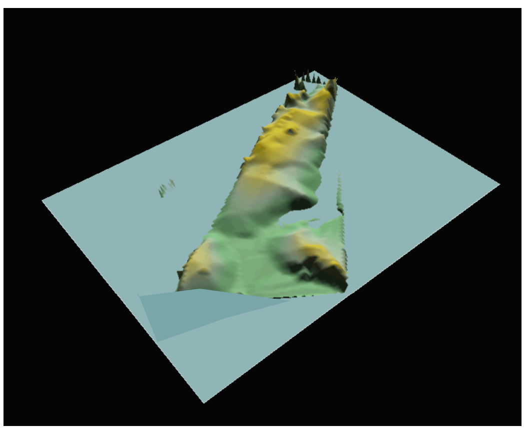
Fig. 14 Tres Rios confluence of Brazos River, Paluxy River and Squaw Creek.



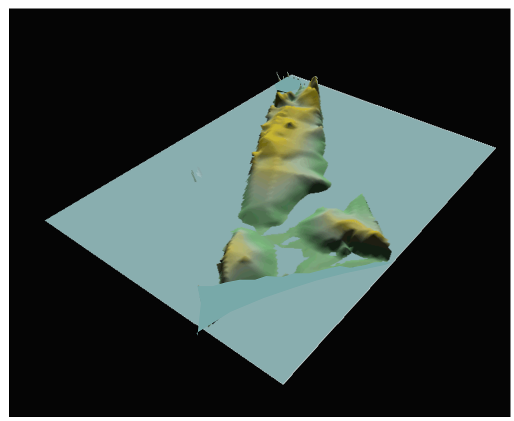
a) Vol. 74.5K T; Gauge 2.8’



b) Vol. 62.7K T; Gauge 3.3’

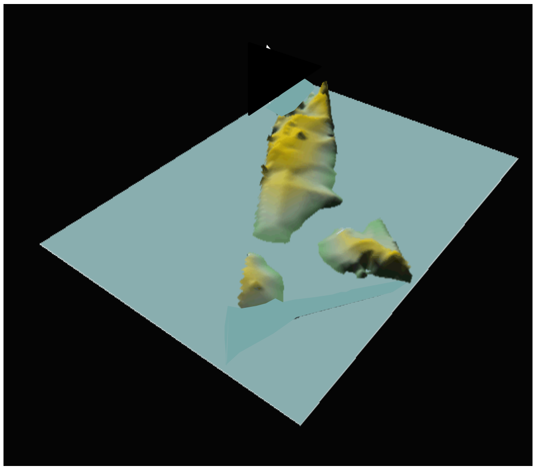


c) Vol 51.4K T; Gauge 3.8’

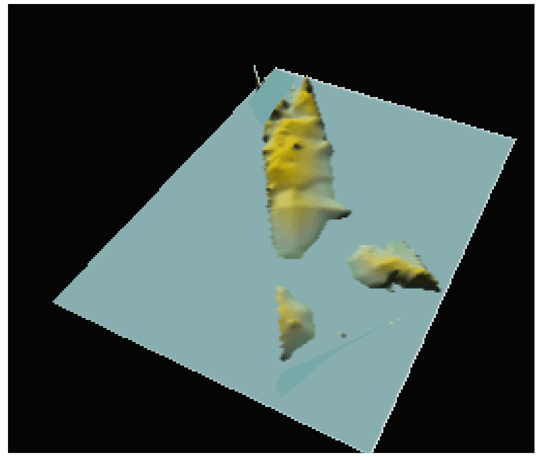


d) Vol. 41.1K T; Gauge. 4.3’

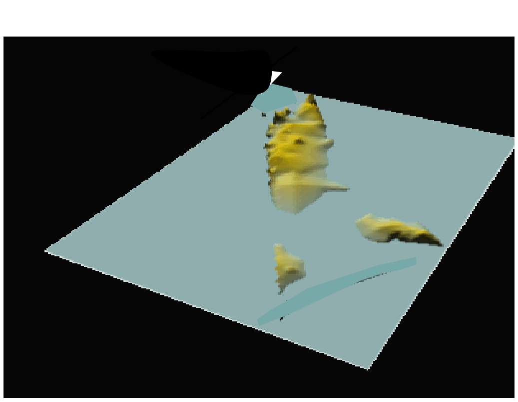
Fig.15 (a – j) Representations of accumulated sediments exposed at incremental increases in flow stage. Volumes are in cubic feet for respective gauge heights.



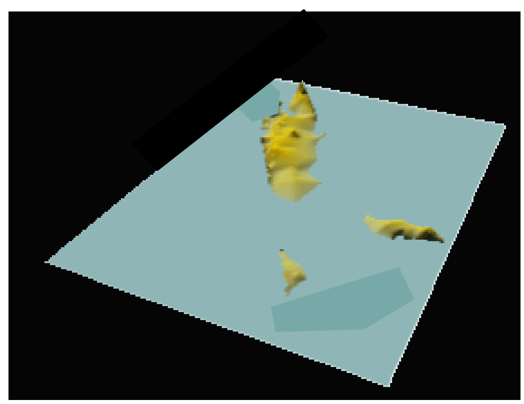
e) Vol. 26.6K T; Gauge 4.8’



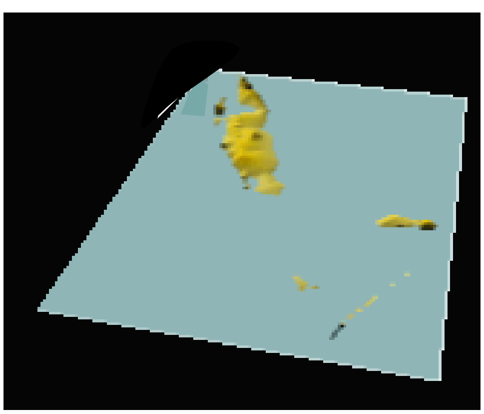
f) Vol. 19.7K T; Gauge 5.3’



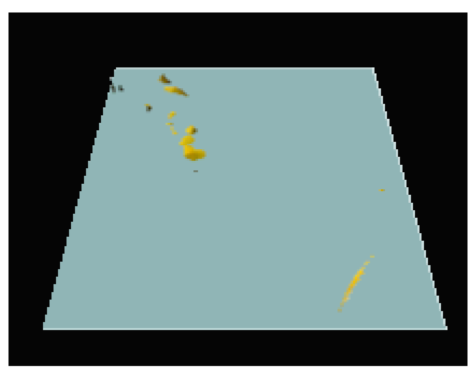
g) Vol. 16.6K T; Gauge 5.8’



h) Vol 9.3K T; Gauge 6.3’



i) Vol. 6.0K T; Gauge 6.8’



j) Vol. 3.0K T; Gauge 7.8’

Figures 16 – 18 are historic aerial images of the Tres Rios confluence for the years 1996, 1984 and 1940 respectively. The images illustrate the morphologic changes occurring in the river channel over time, both pre (1940) and post (1984, 1996) impoundment. Most noticeable in the 1984 and 1996 images is the growth of the point bar on the meander bend of the east bank. Sediment accumulates in the bar and eventually create a diversion in flow at the mouth of the Paluxy that begins to erode the northwestern portion of the channel bar (1984, 1996). Sometime between 1984 and 1996, the channel just upstream of the confluence makes a sharp left turn and creates a new channel cutting southward through the east side of the point bar, separating the point bar from the channel bank. It is undetermined whether this change in the channel location occurred naturally, as the result of turbulence at the confluence during peak flows, or whether it is a man-made diversion.

Fig. 16. 1996 Aerial image of Tres Rios confluence.

Fig. 17 1984 aerial image of the Brazos, Paluxy, Squaw Creek confluence.

Fig. 18   1940 aerial image of the Tres Rios reach of the study area.

An in stream flow report conducted by the firm of Joseph F. Trungale (2005) established flow benchmarks for the three segments of the Brazos Basin in order to establish the current flow conditions and predict disturbances in optimal discharge caused by increased water withdrawals and flow regulation. The study focused on creating a model to represent the impact on river conditions of alterations in flow that would result from full use of all permitted water based on flows considered optimal under natural unregulated conditions. Bar charts were used for each of the three river segments to identify the frequency and magnitude of flow levels which were met or exceeded under naturalized and regulated river conditions, including current withdrawal levels and predicted future flow levels.

The theory that impoundment is not an overall reducer of total sediment delivery to the river mouth was put forth by a USGS study of sediment loads in the Brazos River. It found that there was not a significant reduction in sediment amounts transported to the Gulf of Mexico in spite of 1) significant impoundment upstream; 2) removal of large quantities of sediment by mining operations; and 3) decrease in sediment delivery and runoff from agricultural practices due to a shift in land use for crops. This concept is treated further in a 2002 paper, "Sediment Delivery to the Ocean by Coastal Plain Rivers", (Slattery and Phillips) suggesting that on a basin wide scale, the delivery of sediments to the river mouth may not be drastically reduced by impoundment because basin geometry and channel slope in the lower reaches may offset upstream storage by adding large quantities of sediment in downstream areas. Sufficient slope in contributing streams delivers large amounts of sediment to the Brazos below the Granbury and Whitney reservoirs. Although effects of impoundment can be significant locally, in a basin such as the Brazos, basin characteristics such as slope and drainage area per km^2 have greater impact on lower channel reaches than upstream impoundment (Slattery and Phillips, 2002). Mean coastal plain slope of the Brazos River (is) substantially higher than those of typical coastal plain rivers and is generally considered the source of higher sediment loads and greater portion of sediment load being delivered to the river mouth (Slattery and Phillips, 2002). These findings were the result of the work of Phillips and Slattery on coastal plain river sediment processes for the Trinity, Sabine, Neches, Colorado and Brazos River. Water surface profiles were constructed for the lower river reaches and it was found that mean slopes for the lower river reaches were considerably higher in the Colorado and Brazos, which delivered higher sediment ratios to their respective estuaries.

If, in fact, decoupling occurs between lower and upper basin reaches, the finding of no significant decrease in downstream sediment measurements (USGS) may be insufficient evidence that upper channel reaches maintain sufficient stream power after impoundment to transport sediments efficiently. Much of the sediment storage upstream is in large channel bars that have not been thoroughly examined or quantified, and that have significant effects on channel properties. With the reduction in magnitude and frequency of extreme flood events, the stream power necessary to move large loads of sediment from confluences is not available except during extreme flood events.

Fig. 19 View of the Study area looking north from south end of channel bar at riffle sequence. (M. Slattery, 04/22/06).

It was proposed by Wolman and Miller (1960) that 90% of the total sediment load is removed from the watershed by ordinary discharges that recur at least once every 5 – 10 years, while flows of limited magnitude are incapable of transporting significant loads (Wolman and Miller 1960).

The wide spatial variations in channel morphology and stream power within river systems also leads to considerable variation in channel openness and the degree of navigability in different reaches of the channel under the same gauge heights. The contrast in characteristics of channel morphology between the two areas of the study, the tributary at Tres Rios (Fig. 19) and the reach of the river at the FM 200 Bridge illustrate and support this point. The channel at the tributary junction is narrower, deeper and confined within steeper banks, while the channel near the bridge is shallow and wide with extensive exposures of sandbars and terraces. Lack of confining banks causes the flow to "bifurcate" to an almost braided pattern, to the point that portage of watercraft over extensive gravel areas is necessary, while at the same gauge levels navigation is supported in the Tres Rios tributary junction stretch of the channel. At a gauge height of ~3.8 feet, almost five million cu. ft. of sediment is exposed in the bridge area channel bar (Fig. 20), whereas only 1.1 million cu. ft. are exposed in the main channel bar at the Tres Rios area.

A critical component of determining optimal flow levels for the Brazos is the relation between discharge and sediment transport. A thorough study and construction of a sediment budget for the river, though beyond the scope of this research, is a crucial factor in determining the efficiency of the river to move sediments through the system and maintain channel openness. Locally, the Brazos River below the Granbury reservoir has a significant amount of sediment storage in longitudinal and point pars, particularly at tributary confluences, such as the Paluxy, River, Squaw Creek, Brazos River confluence at Tres Rios . At a gauge height of 4.3 ft, for example, there is ~ 5.5 million ft^3 (or 155,743 m^3) of sediment in the bar systems at Tres Rios and the FM 200 bridge. Using an average bulk density of 1.6 Mg m^3 for sands, we computed ~ 249,188 Mg of sediment is currently in storage in the bar.

Fig. 20 Exposed channel bars at FM 200 bridge area.

A sediment-rating curve constructed for the Brazos (Slattery, 2007) is shown in figure 21. A sediment rating/turbity curve relates turbidity measurements to suspended sediment and can be plotted against discharge levels to calculate total sediment yield. The curve was based on a model for calculating suspended sediment load developed for an ongoing Trinity River study (Slattery, personal communication 2007), as suspended sediment data is not available for the Brazos River. In order to construct the sediment-rating curve for the Brazos, it was assumed that the suspended sediment/turbity relationship of the Brazos was similar to that of the Trinity. Turbidity data for the Brazos was used with suspended sediment measurements for the Trinity and plotted against Brazos River

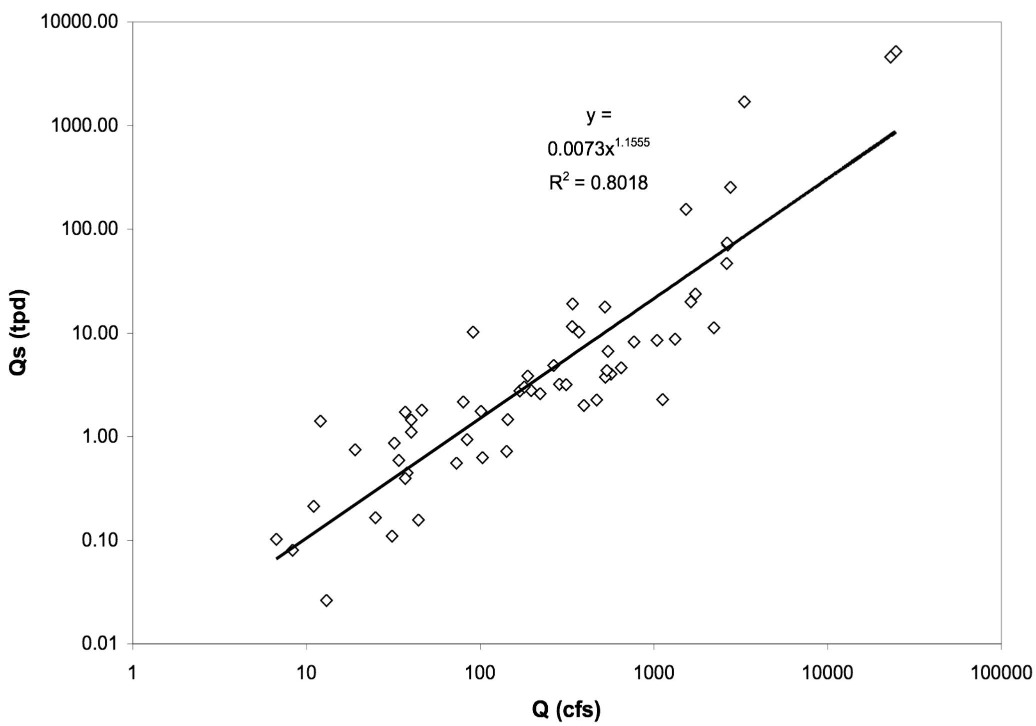


Fig.21 Brazos River Sediment Rating Curve (Slattery, 2007)

discharge levels to construct the sediment-rating curve. Collapsing the sediment-rating curve with the flow duration curve (Fig. 4) allows for an estimate of sediment transport within the Brazos to be made. For this reach, the annual yield is 10,600 Mg, substantially less than the amount of sediment in storage. It should be noted, however, that this sediment yield is computed using suspended sediment data; no bed load is measured in the construction of such curves.

Conclusions

The purpose of this research was 1) to determine a minimal in stream recreational flow level for a reach of the middle Brazos River, and 2) to establish a baseline volume of sediment stored in the channel in order to predict the capacity of the river to transport sediment and maintain an open channel. Based on changes observed in the channel cross-sectional profiles and three-dimensional bar models with incremental increases in discharge, a gauge height of ~ 5.5' – 6.3' (~314 – 650 cfs) is the minimal range that would support recreational use under channel conditions characteristic of those found in the study reach. The estimated annual sediment yield for the Brazos River is approximately 10 Mg annually. The channel bars at the Tres Rios confluence and FM 200 bridge store ~249,188 Mg, of sediment, indicating that in this reach of the river, the Brazos is a storage dominated system, and that flow levels are not sufficient to flush sediments through the channel system.

The impact of impoundment on sediment delivery is not yet fully understood, and for the Brazos River system it is important that a sediment budget be constructed so that the capacity of the river to transport sediments at fluctuating discharge can be established. Calculation of volumes of sediment stored in channel bars is a useful first step in a flow study for the Brazos as it will aid in determining contribution of sediment by tributaries and stream power required to clear the sediments from the channel. Determining sediment transport capacity, or stream power, creates a benchmark for minimal flow stage required to maintain channel openness and navigability.

The results of this study reflect the data collected from channel bar mapping and flow level measurements taken from a one-mile river reach, a very small segment within the 640 river miles of the Brazos River. The large spatial and temporal variability inherent in riverine systems makes extrapolation of information collected at a local scale unreliable as a basis for predicting conditions on a regional scale for river systems. The range of morphologic characteristics observed in the study reach emphasizes this point: riffle and pool sequences, areas of narrow channelized flow, and areas of shallow channels and wide terraces. Additional study of the Brazos river system on a regional scale is necessary to accurately assess the broad range of morphologic conditions and associated flow stages that reflect its dynamics. Understanding the river as a complex interaction of a wide range of fluvial processes is implicit in accurately predicting the impact of future flow regulations on the integrity of the Brazos River.

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Education	Mount Everett Regional High School, Sheffield, Massachusetts, 1969 Associate of Arts, Berkshire Community College, Pittsfield, Massachusetts, 2001 Bachelor of Science, Geology, University of Massachusetts, Amherst, 2004 Master of Science, Geology, Texas Christian University, Fort Worth, 2007
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ABSTRACT

DETERMINING MINIMUM RECREATIONAL INSTREAM FLOW REQUIREMENTS FOR A REACH OF THE BRAZOS RIVER AT GLEN ROSE, TEXAS

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The purpose of this project is to assess the instream flow conditions of the Brazos River from the perspective of determining the levels necessary to maintain the integrity of the river channel as a recreational and ecological resource. The area of this study is the reach of the Brazos River between Lake Granbury and Lake Whitney, located ~48 km southwest of Fort Worth, Texas. Based on changes observed in the channel cross-sectional profiles and calculation of volumes of sediment stored in channel bars, a gauge height of ~ 5.5' – 6.3' (~314 – 650 cfs) is the minimal optimal range that would support recreational use. The estimated annual sediment yield for the Brazos River is ~10.5K tons. The channel bars at the Tres Rios confluence and FM 200 bridge store ~249K tons of sediment, indicating that in this reach of the river, the Brazos is a storage dominated system.