MORPHOLOGY, MECHANISMS, AND PROCESSES FOR THE FORMATION OF A NON-BIFURCATING FLUVIAL-DELTAIC CHANNEL PROGRADING INTO GRAPEVINE RESERVOIR, TEXAS

by

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Abstract

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Non-bifurcating channels in modern reservoirs, tie channels, and the Mississippi River Bird-Foot Delta share a common morphology that is likely due to an underlying common mechanism. Data analysis indicates that the Denton Creek Delta has prograded into Grapevine Reservoir for 56 years, adhering to the buried pre-impoundment channel without alteration. The hydrodynamic mechanism that controls this adherence is that of a turbulent jet. The properties of the turbulent jet create a dynamic two-phase process, whereby prodelta clays and rare mouth bar sands are eroded while the jet contemporaneously builds sandy levees. An upward tapering channel acts to focus and intensify the jet at less cohesive clays

that overlie the preexisting channel. A conceptual model is presented herein comprising basinward tapered levees, the action of the turbulent jet, and rising basin levels, which account for the self-sustained progradation of the delta without bifurcation, and result in a distinctive delta morphology.

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Chapter 1

Introduction

Worldwide, deltas include a wide range of morphologies and sizes. The work of many has led to the basis for understanding the processes that result in various delta morphologies. This chapter introduces concepts regarding linear deltaic end members, including non-bifurcating single-thread channels. Key concepts of delta morphology are explored from a historical perspective. A process-driven overview that explains various morphologies is provided.

1-1 Non-Bifurcating Channels

Non-bifurcating fluvial-deltaic channels are developing in many man-made lakes (reservoirs) in the southern United States. These channels do not follow the classic deltaic processes of mouth bar formation followed by bifurcation (Bates, 1953) (Wright, 1977) .They do not fill all laterally available basin space, instead they prograde basinward. Due to multiple strong geomorphic similarities, these deltaic channels can be considered analogues of, rarer or more remote naturally occurring single-channel deltaic deposits. Tie channels are a common type of these single channel fluvial-deltaic deposits. Tie channels typically connect a river with a shallow water-filled basin such as an oxbow or other floodplain lake (Rowland, 2007) (Rowland, et al., 2009). Tie channels are found worldwide, but the majority are located in remote areas. One larger but geomorphically similar delta is the linear Mississippi River Bird-Foot Delta. The Mississippi River Delta is often considered anomalous or an end member when compared with other marine deltas. The cause of its unique morphology has been highly examined and debated (Bates, 1953), (Galloway, 1975) (Edmonds, 2009).

Single channel non-bifurcating deltas building into man-made reservoirs make excellent laboratories for the study of other similarly shaped delta systems, because they are typically situated near metropolitan areas, and their histories and controlling inputs are often well documented. When the reservoir is important to water supply or flood control, the storage capacity is often studied over time. The Texas Water Development Board (TWDB) has conducted more than 100 such surveys of reservoirs located in Texas and Oklahoma (TWDB, 2013). Historic data such as these can give chronological insight to sediment supply. Additionally, there are often aerial photos or satellite images available that can be used to quantify progradation. Lastly, nearly all reservoirs have gage height monitoring and upstream gage height and flow velocity monitoring for the major streams feeding the reservoir. These data sets can be used in conjunction with images and volumetric surveys to explain the relationships between flow rates, lake effect, and eventual delta morphology (Olariu, 2005) (Olariu & Bhattacharya, 2012).

Despite the extensive data available on reservoirs containing non-bifurcating fluvial-deltaic channels, little is known about the mechanisms that govern how they prograde across basins. Recent literature is available on various aspects of tie channel migration; however, the mechanisms of migration and self-promotion are not fully understood.

1-2 Significance of Non-Bifurcating Channels

Non-bifurcating fluvial-deltaic channels are of interest for several reasons. With rapidly prograding channels, loss of storage acres in a water supply reservoir can outpace storage volume losses predicted with typical deltaic deposition. This is accomplished when delta progradation isolates portions of a reservoir, essentially cutting them off from the main body of water and thus isolating compartments of the lake from general storage capacity and water supply (Figure 1-1). In addition to losing water supply, segregation of a reservoir could affect the accessibility of infrastructure such as boat access ramps or public parks.

Tie channels are common in natural systems and thus should be included in the rock record; therefore, the analogous nature of single channel distributaries in reservoirs provides insight into tie channel rock properties. This insight can also be used in interpretation of the ancient.

These properties would be important in reservoir modeling for the oil and gas industry. Where these channels develop in high accommodation flood plain environments, they may provide a link from the backwater floodplain source rock to high quality reservoir rock deposited in belts of major river channels (Stoner & Holbrook, 2008).

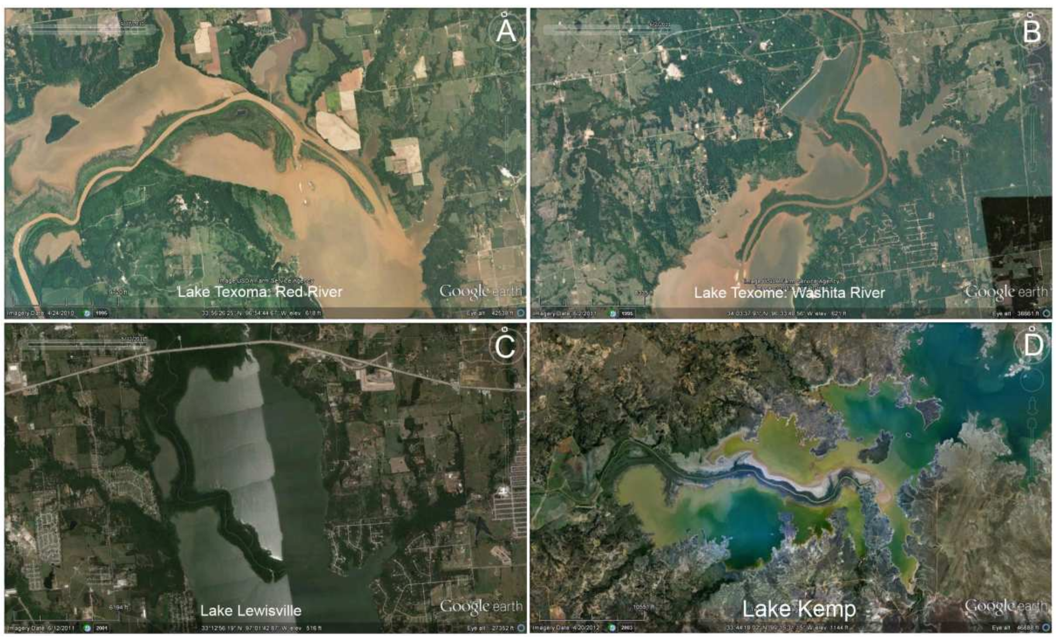


Figure 1-1 Non-bifurcating, single channel deltas in Texas reservoirs (images A-D). Images A and B are satellite images of Lake Texoma deltas formed by the Red River and Washita River, respectively. Images C and D are images of Lake Lewisville, and Lake Kemp deltas, respectively. Image sources: Upper left: Google Earth™, USDA Farm Service Agency. Upper right: Google Earth™, USDA Farm Service Agency, © 2013 Digital Globe. Bottom right: Google Earth™, Texas Orthoimagery Program. Bottom left: Google™.

Lastly, if these channels provide sufficient permeability, they could be aquifers and flow conduits, making them important considerations in aquifer management or waste disposal. The presence of these units means that clay rich floodplain and lake deposits may not always serve as barriers that isolate large fluvial sandstone aquifers, but instead may contain connecting flow paths through thin elongate channel-delta sands.

1-3 Goals

The goal of this work is to accurately depict the delta morphology and bedload distribution within the Denton Creek fluvial-deltaic system of Grapevine Reservoir. Data acquired is used as a tool for determining the mechanism(s) or controlling processes by which single-thread prograding deltas form without bifurcation.

1-4 Background

1-4.1 Deltas

Throughout most of the Holocene, mankind's subsistence has commonly relied on the bodies of sediment deposited where a river meets the sea. These bodies of sediment known as deltas have provided a fertile landscape for numerous civilizations. Worldwide delta building in response to relatively stable sea levels is also coincident with the advent of agricultural based human settlements (Stanley & Warne, 1994; Stanley, 1997). The word "delta" as used to describe the body of sediment that accumulates at a river mouth has typically been accredited to Herodotus, a 5th century B.C. historian. Whether or not he actually coined the word to apply to deltas in general is subject for debate (Celoria, 1966); however, he did use the word “delta” to refer to deposits of the Nile River upstream of the mouth that the Egyptians inhabited (Herodotus, appx. 440 B.C.).

Deltas form whenever a sediment-carrying stream meets a quiescent basin filled with water. They are typically thought of and described as having lobate geometry, but other forms exist such as the linear Mississippi Bird Foot Delta. Much has been written on the diverse processes governing the general formation of deltas. Gilbert addressed the process by which deltaic sediment is deposited in a step-wise fashion based on grain size, as the velocity of a river slows when entering a lake. He also addressed the effect of basin-ward generated energies on deltaic deposits and the general notion that deltas coarsen upward in stratigraphic succession (Gilbert, 1885) (Gilbert, 1890). Gilbert is also acknowledged for establishing the concept of topset, foreset, and bottomset beds; these terms remain a part of sequence stratigraphy nomenclature today.

1-4.2 Delta Morphology

Delta morphology is dependent on multiple factors including sediment load, sediment size, fluid properties, and energy of basin processes associated with the reworking of delivered sediment. A central paradigm relating to controls on sediment delivery is jet theory, established by Tollmien in 1926 (Bates, 1953). Jet theory describes the transfer of energy of a radially symmetric turbulent jet of fluid emitted from an orifice as it enters a still body of similar fluid. Entering the body of fluid causes jet spreading and mixing with the basin water at the margins of the jet; this results in a Gaussian velocity profile across the jet (Figure 1-2).

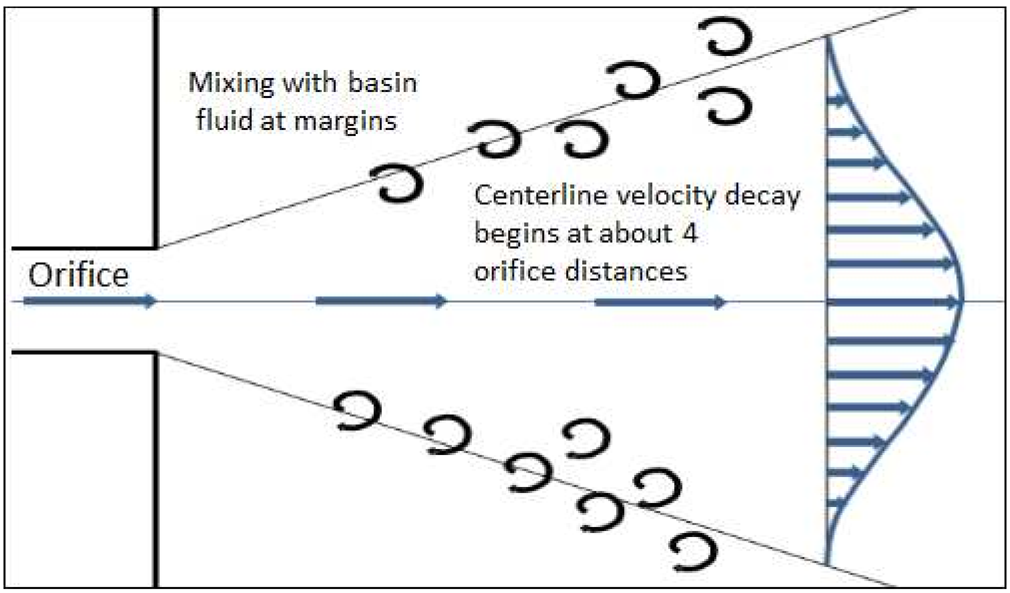


Figure 1-2 Turbulent jet spreading and velocity decay model.
Model shows hypothetical turbulent jet spreading which occurs when a high velocity jet of fluid is emitted from an orifice and enters a basin filled with similar fluid. Circular arrows represent mixing with basin fluid at jet margins. Blue arrows represent Gaussian velocity decay at 4 orifice distances from the mouth. Modified from Bates 1953 and Wright 1977.

Application of this theory to various basin shapes, sediment types, and fluid properties results in a range of depositional geometries (Bates, 1953) (Axelsson, 1967) (Wright & Coleman, 1974) (Hoyal, et al., 2003) (Rowland, et al., 2009) (Falcini & Jerolmack, 2010). This theory had been expanded upon by many to include confounding factors such as a hydraulic head where the jet enters the basin, hypopycnal flows (inflow less dense than basin fluid), hyperpycnal flows (inflow more dense than basin fluid), and homopycnal flows (inflow and basin with equal densities), (Figure 1-3) and the resulting delta geometries that each type flow predicts (Bates, 1953).

For river-dominated systems, Wright added the effects of bed friction based on different basin configurations to inertia dominated turbulent jets while contrasting different effluent buoyancies. This allowed for further explanation of jet spreading and resulted in three fundamental geometric delta models predicting levee growth, bar mouth growth, and distributary bifurcation (Wright, 1977).

One of Wright's models, the buoyant effluent model, conforms to long non-bifurcating channel deltas; however, this model applies to fresh water entering a salt water basin where the hypopycnal jet is supported by a density contrast between the fluids. Elongate non-bifurcating channels also occur in freshwater lakes where hypopycnal flows do not exist (Falcini & Jerolmack, 2010). Roland and Dietrich commented on how Wright's bed friction dominated model was morphologically very similar to the Raccourci Old River tie channel morphology, particularly at the channel mouth. This model does result in subaqueous levee growth; however, it also results in middle ground bar formation which leads to bifurcation (Rowland & Dietrich, 2005).

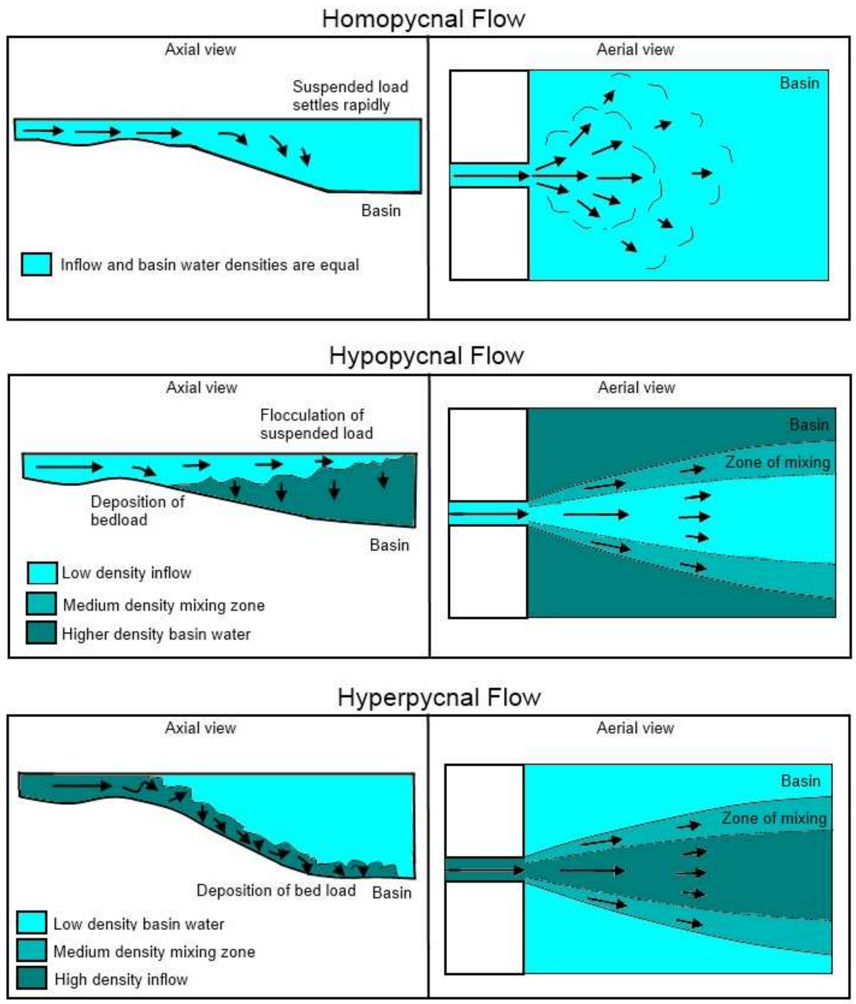


Figure 1-3 Diagrammatic flows and spreading patterns based on relative incoming and basin fluid densities for homopycnal, hypopycnal, and hyperpycnal flows. Axial and aerial views are shown for each type of spreading. Arrows in axial views represents particle motion within the flow. Arrows in aerial views represent velocity profiles. Relative fluid densities in all frames are color coded with darker colors representing higher densities. Modified from Bates 1953 and Boggs 1995.

Further complications of delta geometries occur when tidal or wave energies act upon the depositional body. A widely referenced model that categorizes large modern marine deltas is based on three main processes (Galloway, 1975). It incorporates the flux of fluvial sediment input along with the influence of wave and tidal energy. In this model, different modern delta morphologies are explained as either being dominated by one of these processes (end members) or by being the product of any combination of the three processes (Galloway, 1975). Based on this model, the non-bifurcating linear morphology of the Mississippi River is due to river domination (Figure 1-4).

Mouth bar growth results in bifurcation and increased distributary channels. However, river dominated deltas are known for fewer bifurcations and distributary channels. Recent studies specifically focus on the causes of mouth bar growth and the relationship between mouth bar growth and bifurcation. Several river dominated delta morphologies were modeled using Delft3D. Analysis of modeling results indicates that river mouth bars form in response to decreasing centerline sediment transfer rates. The decrease in transfer rate is associated with the vertical expansion of a turbulent jet and initiates mouth bar growth. As mouth bar growth continues, subaqueous levees flare outward around the bar, which eventually results in bifurcation (Edmonds & Slingerland, 2007). Continued modeling efforts focused on cohesion and its effect on river dominated deltas and again used Deft3D. The authors found that high cohesive sediment load led to more stable levees, increased jet focus, and led to cohesive mouth bar erosion. This limited the development of bifurcating mid-channel bars and thus provided a mechanism for bird-foot like deltas (Edmonds & Slingerland, 2010). This recent work provides a fundamental concept by which other single channel prograding deltas may form.

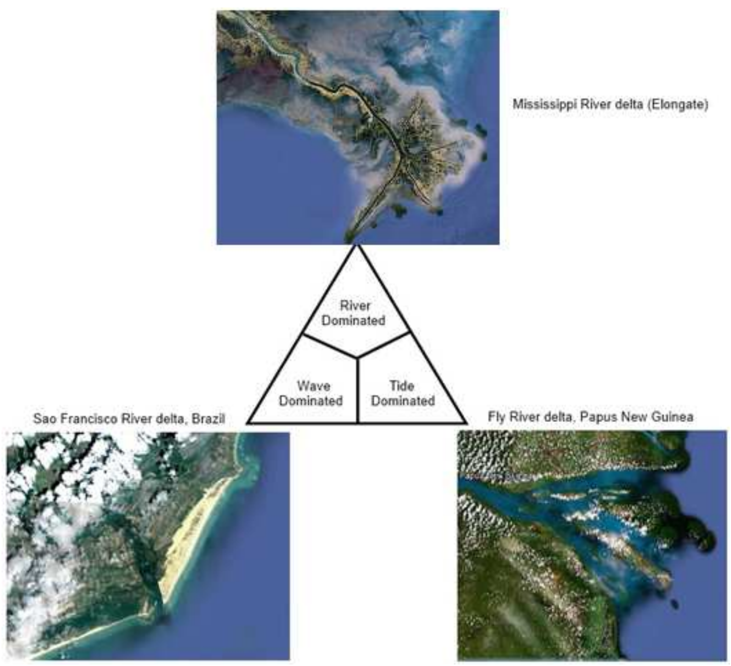


Figure 1-4 A ternary diagram based on the three primary energy regimes, which either deliver or rework sediment, and images of the corresponding end member morphologies. Top image is of the river dominated Mississippi River Bird-foot Delta. Bottom left image is of the wave dominated Sao Francisco Delta. Bottom right image is of the tide dominated Fly River Delta. Modified from Galloway 1975. Satellite images sources: Top: Google Earth™, Data SIO, U.S. Navy, NGA, GEBCO, 2013 © TerraMetrics, NOAA. Bottom left: Google Earth™, USGS 1969; Bottom Right: Google Earth™, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, © 2013 TerraMetrics.

1-4.3 Tie Channels

Another smaller but closely related type of sediment deposit is known as a tie channel (Figure 1-5). Until very recently tie channels have been largely undescribed in the literature. A tie channel by definition is capable of two-way flow and connects (ties) a river with a shallow water filled basin such as an oxbow (Figure 1-5, B&D) or other floodplain lake (Figure 1-5, A&C). Tie channels rapidly prograde basin-ward by sedimentation along the margins of a turbulent jet.

Figure 1-5 Four images of naturally occurring tie channels (A-D).
Frames A, B, C, and D are images of tie channels off the Ouachita River, Mississippi River, Grijalva River, and the Fly River respectively. Images A and C show tie channels building into floodplain lakes; images B and D show tie channels building into oxbow lakes. Satellite images sources: Upper left: Google Earth™, USDA Farm Service Agency. Upper right: Google Earth™, USDA Farm Service Agency. Bottom right: Google Earth ™, © 2013 TerraMetrics. Bottom Left: Google Earth™, ©2013 GeoEye.

Tie channels typically prograde without bifurcating and have low sinuosity. They form a clay rich prodelta and their V-shaped channels erode into the cohesive prodelta as the tie channel progrades basinward (Rowland, 2007). Tie channels with most or all of these characteristics have been examined off the Fly River, Papua New Guinea, off Birch Creek, Alaska, on the Raccourci Old Oxbow Lake, Louisiana (Rowland & Dietrich, 2005) (Rowland, 2007) and in the Grijalva and Usumacinta River Basins, Tobasco State, Mexico (Hull & Holbrook, 2012).

1-4.4 Linear Channels in Reservoirs

Fluvial-deltaic channels building into many modern man made reservoirs (Figure 1-1) have strong geomorphic similarities to tie channels in natural systems as well as components of several of Wright's models (Wright, 1977).The height of fluvial-deltaic channel levees decrease basinward. These channels have subaqueous levees that become subaerial over time. They rapidly prograde basinward, and are not substantially reworked by waves or tides. They do not migrate laterally and show little point bar growth (Rowland, 2007). Channels with this morphology are quite common in man-made reservoirs (Stoner & Holbrook, 2008).

One particular linear fluvial-deltaic channel recently studied is that of the Red River where it flows into the west end of Lake Texoma on the

Oklahoma-Texas border. Recently, the factors controlling the Red River Delta (Figure 1-1, D) were examined using wavelength reflectance from satellite images. It was argued that density contrasts between the Red River and the Lake Texoma Basin have established a permanent hyperpycnal flow, and that this in combination with pre-existing basin topography determined the direction of delta progradation. The authors believe that shallow portions of the basin are bypassed due to low gradients and remain unfilled by sediment; whereas, the preexisting thalweg provides the maximum basin gradients, and it is this gradient that the density flow follows and progrades along. It was also argued that the overall delta shape was determinant upon whether the recent history has had a large flow event or has been dominated by low flow over a period. Large flow events have resulted in periods of delta elongation; whereas, low flow periods have resulted in periods of a lobate form (Olariu and Bhattacharya et al., 2012). A similar channel exists in Grapevine Reservoir located in Tarrant and Denton Counties, Texas, and was the subject of this study.

1-5 Study Area

Grapevine Reservoir, also known as Grapevine Lake, was made by the damning of Denton Creek in 1952 (Figure 1-6). The primary uses of the reservoir are municipal water supply, recreation, and flood control.

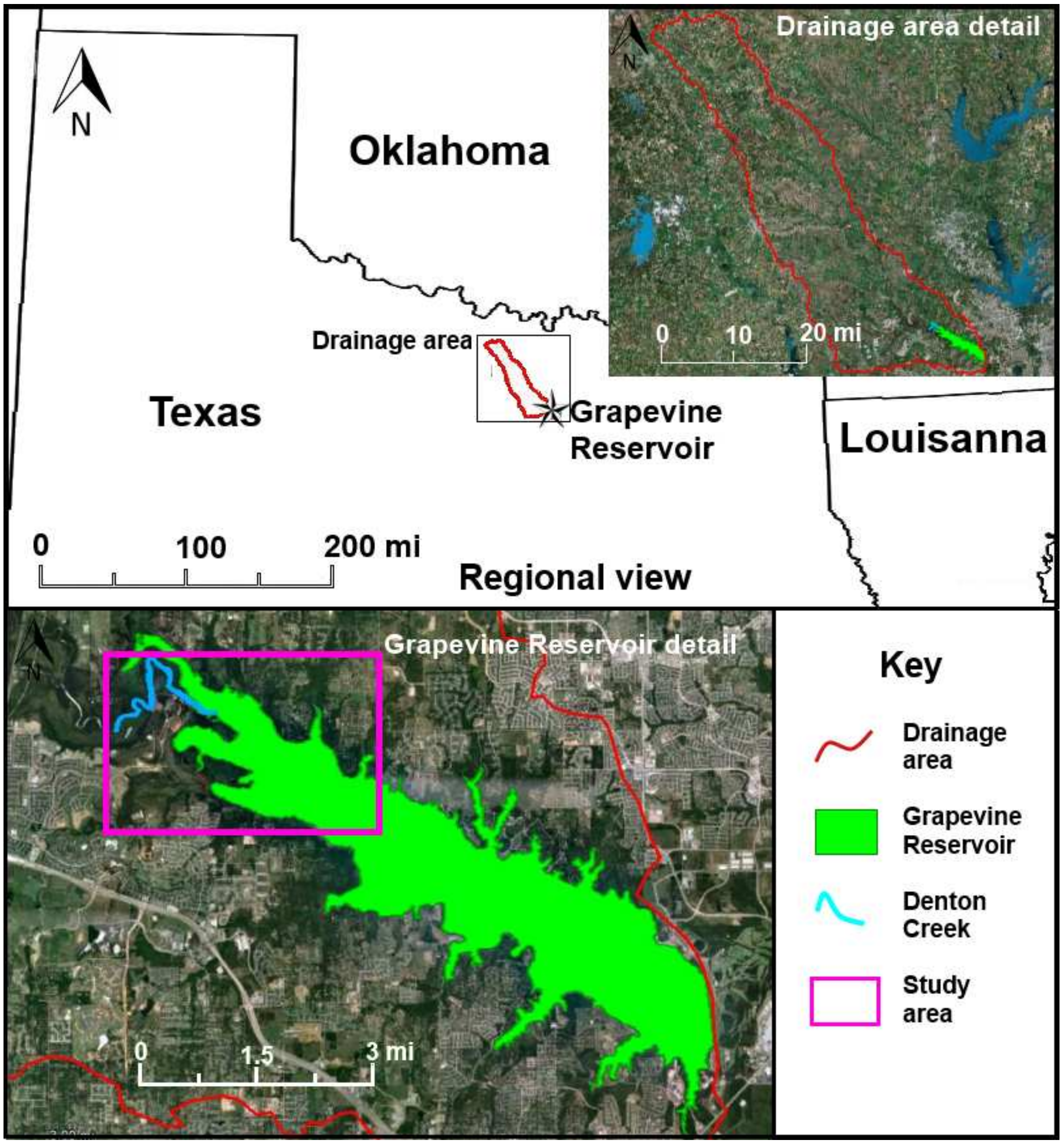


Figure 1-6 Map and images showing the location and geographic extent of the Grapevine Reservoir drainage area, Grapevine Reservoir, Denton Creek, and the study area. Upper image is of boxed area in map and shows the location and extent of the Grapevine Reservoir drainage area (red outline). Lower image is a detailed view of the lake surface area (green fill), study area (pink box), and Denton Creek within the study area (blue). Image sources: Top: Google Earth™, ©2103 TerraMetrics. Bottom: Google Earth™ 2013

The reservoir is owned and operated by the U.S. Army Corps of Engineers (USACE) (Solis, et al., 2011). The main supply of water is Denton Creek which flows into the reservoir in the northeast corner. The total drainage basin for Grapevine Reservoir is about 268 mi^2 (695 $km^{2)}$ of which more than 90% of the area drains to the reservoir via Denton Creek (NCTCOG, 2010).

Because Grapevine Reservoir is a municipal water supply, loss of storage capacity is of primary concern. Throughout the history of the reservoir, storage capacity has been lost, primarily from the sediment deposited by Denton Creek. Both the USACE and the Texas Water Development Board (TWDB) have studied reservoir storage space since impoundment. Since 1952, the surface acres of the reservoir have been reduced by 9.1%, from 7,377 acres (2.83 ha) to 6,707 acres (2.43 ha), and the conservation storage has been reduced by 13.5% from 188,550 ac-ft (2.32×10^8 m^3) to 163,064 ac-ft (2.01×10^8 m^3) (Austin, et al., 2002) (Solis, et al., 2011). Satellite image examination shows that the Denton Creek Channel and northern levee advanced more than 3000 ft (914 m) between 1995 (Figure 1-7, Top) and 2011 (Figure 1-7, Bot). The minimum delta growth between these images is highlighted in yellow.

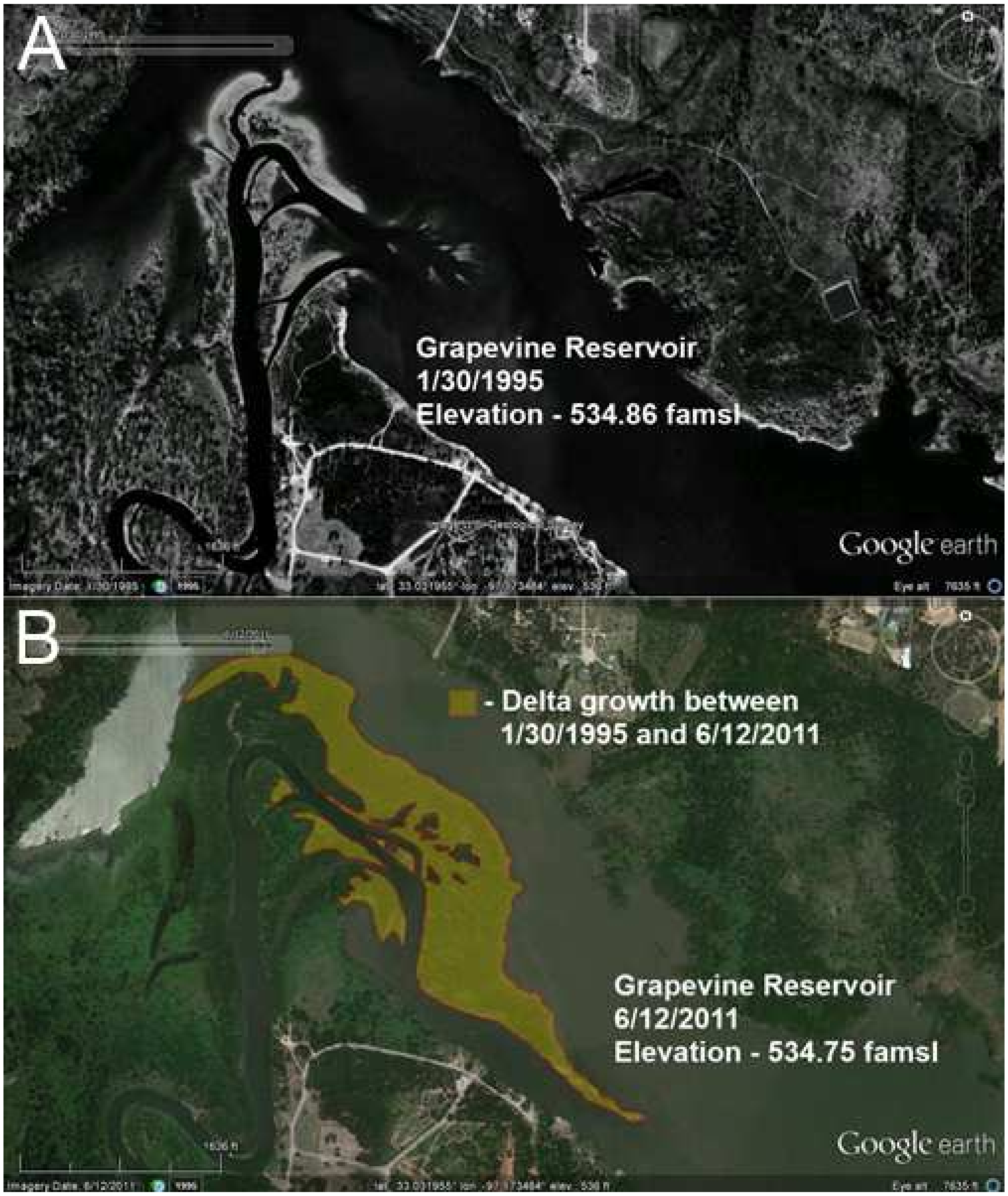


Figure 1-7 Recent growth of the Grapevine Reservoir Delta (images A and B).
Image A is of Grapevine Reservoir in 1995. Image B is of Grapevine Reservoir in 2011.
Subaerial growth between 1995 and 2011 is indicated by yellow overlay on image B.
Satellite images sources: Top Google Earth™, USGS 1995. Bottom: Google Earth™.

1-6 Hypotheses

Data collected will either support or refute the hypothesis that the distributary channel is non-bifurcating because sand load is not reaching the mouth of the river. An alternate hypothesis is that mouth bar sands do accumulate, but not to the point of bifurcation due to infrequent large flow events removing the mouth bars. In the latter case, sand grains will be present in the prodelta sediments basin-ward of the mouth of Denton Creek. The null hypothesis is that the distributary channel is non-bifurcating; however, this is not related to mouth-bar sand accumulation.

Chapter 2 Methods

This chapter addresses site selection and data collection methods used in the analysis of the mechanism(s) and processes responsible for the single channel prograding delta in Grapevine Reservoir. These methods include the collection of data using bathymetry equipment, gouge tools, and bottom sampling tools; and the use of publically available data sets and images. This is followed by the methods used to process the data to generate maps, calculate channel dimensions, and evaluate changes over time of the prograding delta in Grapevine Reservoir.

2-1 Site Selection

Selection of a study area was accomplished by evaluating satellite images available through Google Earth™ for linear prograding channels forming in both natural systems and in reservoirs. Older satellite images available through Google Earth™ were examined to establish which channels are rapidly prograding. This allowed for elimination of potential study areas where the deltaic channel appeared static or had limited growth over the span of available images, typically 20 to 30 years.

Both, the Denton Creek Delta in Grapevine Reservoir, and the Washita River Delta in Lake Texoma were visited by boat as a part of the study area selection process. At the time of the visit, Lake Texoma was 2.9 ft (0.88 m) below normal pool at 614.10 feet above mean sea level (famsl) (187.17 mamsl) and Grapevine Reservoir was 0.74 ft (0.23 m) above normal pool at 235.74 famsl (71.85 mamsl)(USGS, 2012). The delta systems of both lakes were overviewed and the presence or absence of subaqueous levees was noted by using a Hummingbird 727 LCD depth finder. Both deltas were randomly bottom sampled with a gouge sampler attached to a Dutch auger system, to determine general composition. Additionally, the fluvial-deltaic system was evaluated for accessibility by boat.

Both deltas were found suitable. Grapevine Reservoir was selected as the study area based on greater accessibility of the fluvial-deltaic system by boat, and on proximal location. The study was carried out from September 2012 to December 2012.

2-2 Instrumentation

2-2.1 Bathymetry

A bathymetric survey of the Denton Creek prodelta was performed to map subaqueous features of the prodelta. Bathymetry measurements were made with a SurveyCase SC-200™ (Figure 2-1, B&C) and accompanying software, Smart Survey version 6.0.0 and Depthpic 5.0.1 manufactured by Specialty Devices Inc. The SurveyCase incorporates a 200 kHz transducer along with a WAAS beacon and a Differential Global Positioning System (DGPS) receiver. The system marries X-Y data with a potential accuracy up to 1.64 ft (0.5 m) with Z data of resolution up to 0.3 in (0.75 cm). This system is widely used by the United States Geological Survey (USGS) (Linhart & Lund, 2006), the Texas Water Development Board (TWDB) (Solis, et al., 2008), and other government agencies to conduct bathymetric surveys.

2-2.2 Sampling

Bottom samples and surface samples were retrieved with manual coring and sampling devices. A Dutch auger system was used for manual coring of thick sections (Figure 2-1, A). The device is capable of acquiring multiple “stacked” cores at 0.328 ft (1 m) intervals and can penetrate to depths on the order of 33 ft (10 m).

Instruments used for retrieving subaqueous sediment (Figure 2-1, D) include a bottom sampling pole with a one-cup (237 mL) scoop attachment, and a polyvinyl chloride (PCV) check valve apparatus that could be attached to the Dutch auger system for retrieval of shallow suction cores. Both devices were created with over-the-counter parts available at most hardware stores. The bottom sampling pole and scoop is capable of acquiring a one-cup sample of bottom sediment at water depths of up to 24 ft (7.3 m). It was the tool used in acquiring all bottom samples. The PCV check valve apparatus was tested and found to be marginally effective and was only used once during the study.

Figure 2-1 Data collection tools: images (A-D).
Image A shows a Dutch auger with gouge attachment. Image B shows the boat used for bathymetry data collection. In this image the GPS receiver is pole mounted over the transducer and is located on the starboard side, and the WAAS beacon is pole mounted on the bow. Image C shows the SurveyCase SC-200™, and D shows sampling tools.

2-3 Data Acquisition Procedures

2-3.1 Bathymetry Data Collection

Bathymetry data were collected and used to generate quality maps to aid in the identification of subaqueous levees, other bedforms, and the extent of the prodelta. The bathymetry data collection consisted of 73,533 X, Y, and Z data points (Figure 2-2) and covered an area of about 1.4 mi^2 (3.62 km^2).

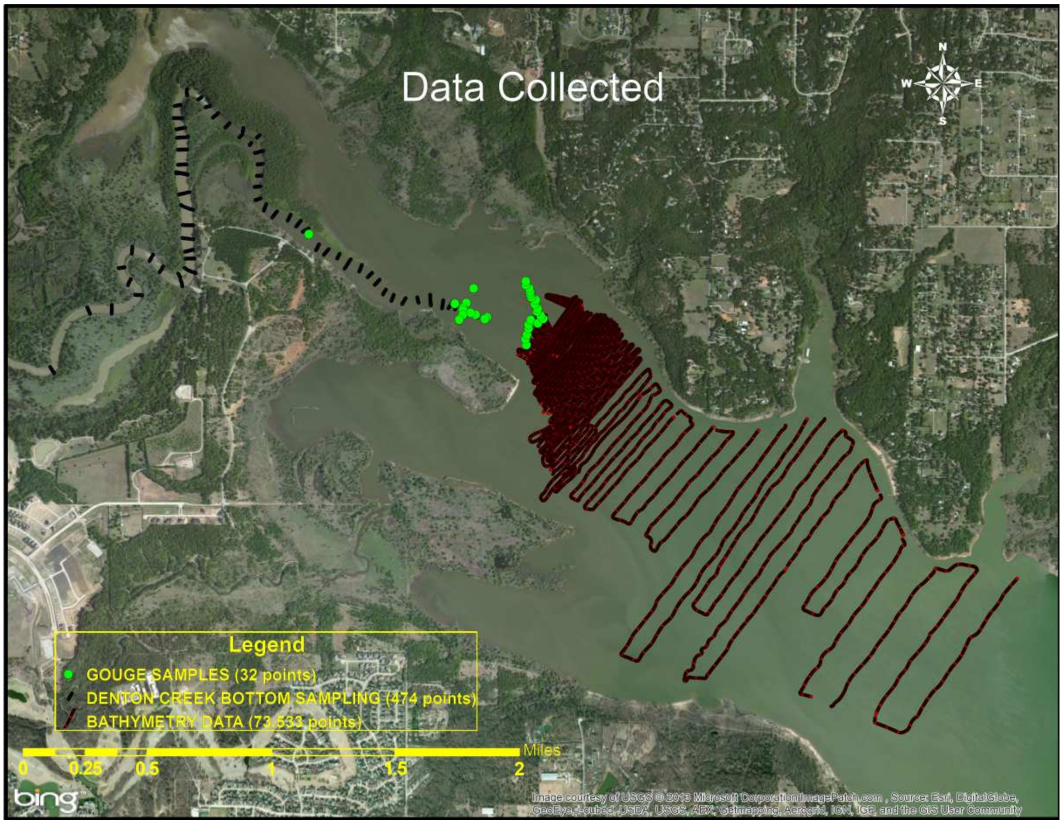


Figure 2-2 Map view of all data collected.
The path of bathymetry data collection is indicated by red lines. Gouge data is indicated by green dots. Short purple lines indicate bottom sampling cross section locations. Map generation: Esri® ArcMap™ 10.1. Image courtesy of USGS © 2013 Microsoft Corporation ImagePatch.com.

Bathymetry data was collected using the SurveyCase SC-200™ system manufactured by Specialty Devices Inc. Components of the system were mounted on a 1994 model 24-foot Javelin FS boat with a 1995 Evinrude 150 hp outboard motor (Figure 2-1, B). The transducer pole was mounted portside and adjusted in calm water so that the draft was 0.5 ft (0.15 m). A hand held level was used to set the transducer pole to vertical and the transducer pole was held in position using a ball clamp, two braces, and a guy-rope system. The WAAS beacon was connected to a GPS unit. Its function was to improve XY accuracy by correcting for a variety of atmospheric conditions. The WAAS beacon was mounted 8 ft above the bow deck for improved signal reception. The outboard motor was operated at idle speed, and all data were acquired at speeds of less than four knots.

The longitude and latitude of each transducer ping was recorded by the SurveyCase SC-200™ using the WGS 84 coordinate system. With the sampling rate set to 50 kHz, the corresponding subaqueous bottom elevation was recorded by the device as a continuous digital image of depth between the water surface and the bottom. Depth was automatically calculated based on the two-way travel time of each ping utilizing the settings for draft (0.5 ft) and the speed of sound in water, which was set to 4,859 ft/s (1,481 m/s).

Data acquisition paths were predominately perpendicular to Denton Creek flow direction (along the prodelta strike). Spacing and variations in the path of acquisition were based on minimum navigable depth, obstacles, and level of bottom structure detail desired. Spacing of approximately 30 ft (9.1 m) was used at the shallowest locations because initially the goal was to identify sand deposits and any levee development.

As the survey progressed, the approach was modified due to a lack of bottom surface features and topographical change. Eventually, the approach was modified to locate the extent of the prodelta by finding structures that pre-existed impoundment. The maximum path spacing in the deeper portions of the survey was approximately 600 ft (183 m).

2-3.2 Gouge Sample Data

A Dutch auger was used to identify subsurface sediment types based on the USDA textural soil classification by using a field testing “sense of touch” technique (Thien, 1979). Soil typing was used to gain insight into flow regimes and processes involved in levee and prodelta development. In addition to soil classification, organic percentage was estimated and, if identifiable, type of organic material was noted. Other irregularities were also noted. In total, 32 individual gouge core locations were sampled (Figure 2-2).

Each gouge core was sampled using the Dutch auger system. The surface location of each gouge hole position was recorded using a Garmin etrex Vista HCX handheld GPS. The longitude and latitude of locations were recorded using the WGS 84 coordinate system. The surface elevation of each hole was measured and logged in feet relative to water surface. This distance was later added to or subtracted from the daily mean water surface recorded by USGS gage 8054500 to derive the surface hole location in famsl.

Two cross sections consisting of multiple gouge cores were performed perpendicular to the direction of Denton Creek flow and levee development. One cross section was located upstream of the Denton Creek mouth and one is located basinward of the mouth. Additionally, several individual gouge cores were sampled. Each gouge core consisted of at least one 3.28 ft (1 m) section and was sample tested at 0.33 ft (0.1 m) intervals. When possible, gouge holes were reentered for successive 3.28 ft sections and were also sample tested at 0.33 ft intervals. Most subaqueous locations consisted of highly liquid clays or unconsolidated sand intervals. For this reason, hole collapse was a significant issue and made reentry difficult or unreliable. Therefore all subaqueous gouges consist of one section only.

2-3.3 Bottom Sample Data

Similar to gouge sampling, bottom sampling was used to identify subaqueous sediment types based on the USDA textural soil classification by using a field testing “sense of touch” technique (Thien, 1979) in order to map sand distribution within Denton Creek. In total, 474 bottom locations were sampled within Denton Creek (Figure 2-2).

For all locations, bottom samples were obtained using a fiberglass extendable pole with a one cup (237 mL) scoop attachment. The pole with attachment was marked in one foot increments. For each bottom sample location, the vertical distance relative to feet below the water surface was measured and logged. This distance was later added to or subtracted from the daily mean water surface recorded by USGS gage 8054500 to derive the bottom sample elevation in famsl. For each sample up to one cup of material was retrieved. This material was checked for consistency and the sediment type was field tested and logged in the same manner as described for gouge sampling. Each bottom sample was part of a set of samples taken in cross sectional fashion perpendicular to the flow direction of Denton Creek. Each cross section consisted of a minimum of 6 sampled locations.

Through trial and error, it was determined that the best method for sampling cross sections on the water with sufficient X-Y accuracy (non-overlapping errors) was to record the beginning and ending points of the cross section at the water-shore contact with the boat anchored to the shore. This provided the handheld GPS a stable enough location to acquire an accurate position. The longitude and latitude of all cross sectional endpoint locations were recorded using a Garmin etrex Vista HCX handheld GPS set to the WGS 84 coordinate system. All endpoints were recorded with an accuracy of ≤9 ft (2.7 m). Bottom samples were collected on approximately 20 ft (6.0 m) spacing. This distance was reduced if bottom elevation changed rapidly along the cross section, or if neighboring cross sections showed anomalous changes. The distance was increased in sections of the river where the channel bottom was more uniform or where obstacles prevented narrower sample intervals.

Samples between endpoints were taken in fractions of river width by visual estimate. The recorded latitude and longitude of the cross sectional end points were later used to extrapolate the latitude and longitude for all points between the endpoints.

2-3.4 Combining Data Sets

Historic data for Grapevine Reservoir surface elevation (USACE, 2013) were acquired back to reservoir fill-up (Figure 2-3). The USGS recording gage 8054500 for Grapevine Reservoir surface elevation is located at the northeast end of the dam. Historic data were also acquired for Denton Creek flow velocities (USGS, 2013) dating back to before reservoir impoundment (Figure 2-4). This gage is located upstream of Grapevine Reservoir near the town of Justin Texas.

Multiple satellite images of successive dates were accessed through Google Earth™ and bing™. Single frame aerial photographs, aerial mosaics, and high resolution orthoimages were acquired through the USGS (USGS, 2013). Satellite images and aerial photos were cross referenced with gage data for evaluation purposes.

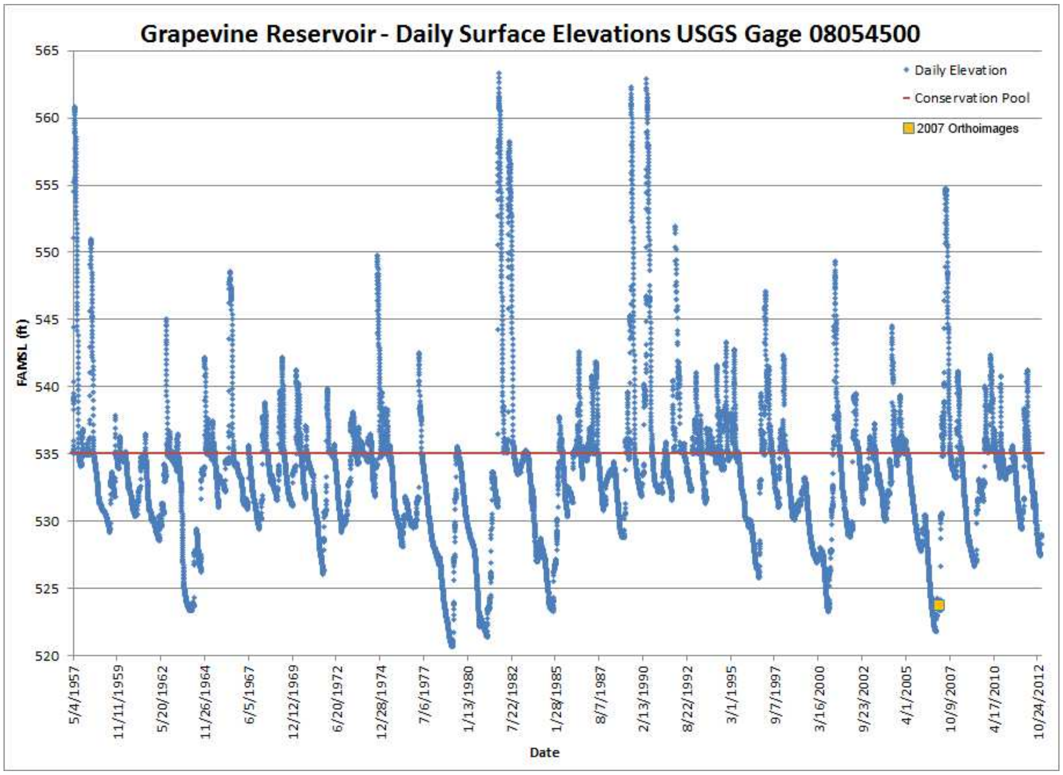


Figure 2-3 Historic Grapevine Reservoir surface elevation data.
Daily elevation of Grapevine Reservoir as recorded by USGS gage 08054500 is indicated by blue dots. Conservation pool is indicated by a red horizontal line. Elevation at time of the 2007 orthoimages is indicated by a yellow square

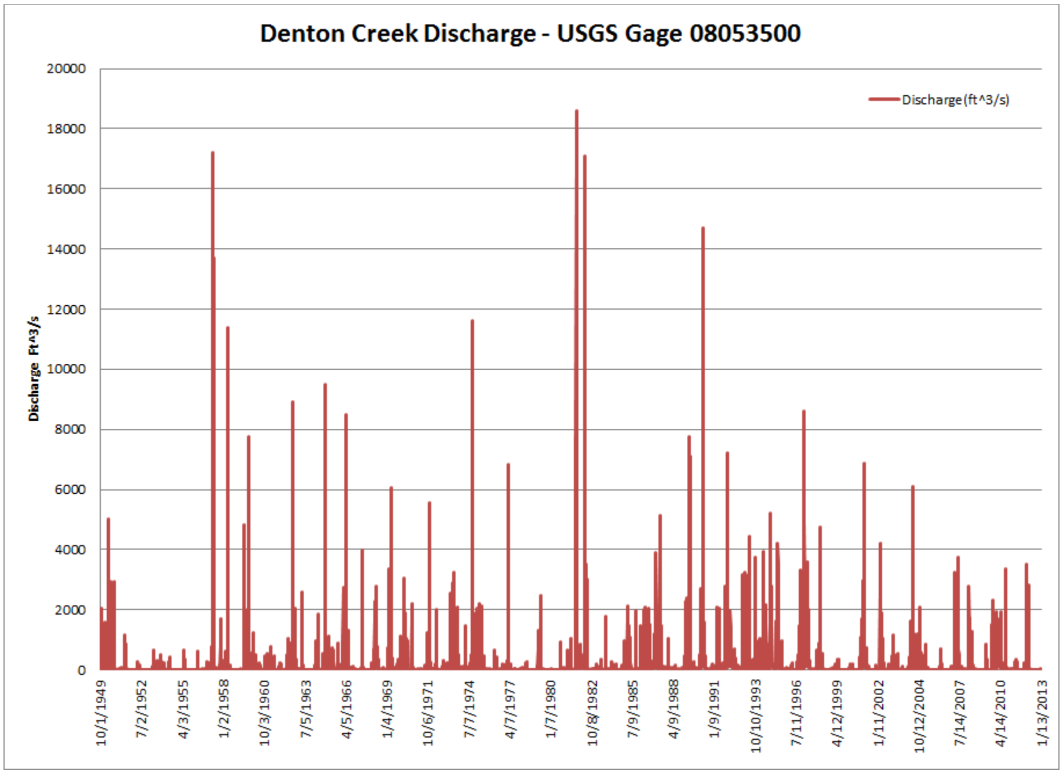


Figure 2-4 Historic Denton Creek discharge data.
Red bars indicate discharge rates as recorded by USGS gage 08053500.

2-3.5 Delineation of Denton Creek Mouth

The exact location of the mouth of Denton Creek is dependent on the elevation of Grapevine Reservoir and is subject to interpretation. For the purpose of data collection and analysis a series of high resolution orthoimages were used to delineate the approximate location of the Denton Creek mouth (Figure 2-5). These images were taken on 2/7/2007, during a Grapevine Reservoir historic low as indicated by the yellow square (Figure 2-3). All distances within this document are reported relative to the mouth at this time, and are reported as thalweg distances upstream of the mouth. Distances and areas within this document were measured using distance tools in Esri® ArcMap™ 10.1, and Google Earth Pro™.

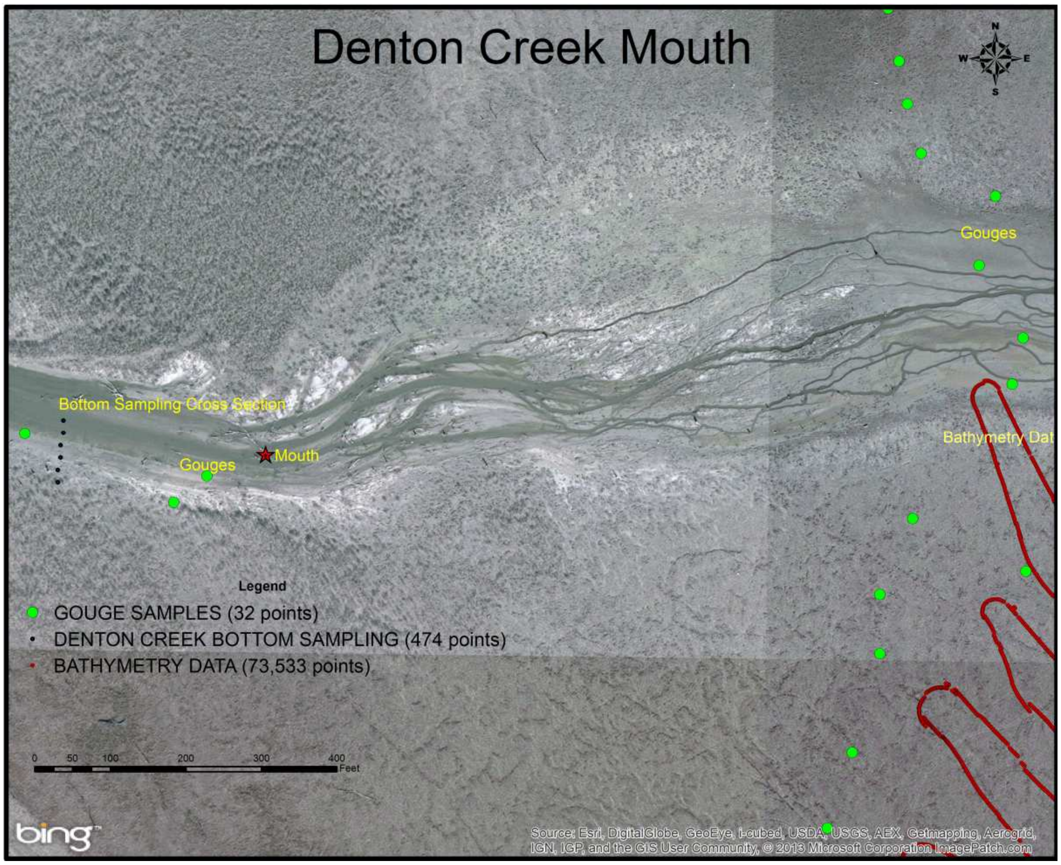


Figure 2-5 Satellite image of Denton Creek mouth.
The star in the image indicates the map location of the Denton Creek Mouth established for map measured distances. Map generation: Esri® ArcMap™ 10.1. Orthoimage source: USGS Earth Explorer, North Central Texas Council of Governments NCTGOG.

During data collection, low reservoir elevations prevented acquisition of bottom sampling data about 210 ft (64 m) immediately upstream of the mouth, although single point gouge data were collected as close as 90 ft (27 m) upstream of the mouth. For the same reasons, all gouge data basinward of the mouth were collected no closer than about 800 ft (243 m) (Figure 2-5).

2-4 Data Processing

2-4.1 Bathymetry Processing

Bathymetric image data recorded by SurveyCase SC-200™ representing 73,533 individual pings was manually digitized using Depthpic 5.0.1. Manual digitization was performed to eliminate items that were misinterpreted as the bottom by the device's automatic bottom picking algorithms. These items include fish, trees, or other debris lying on the bottom or within the water column. Manual digitization was also used to smooth rhythmic bottom signatures caused by waves rolling or pitching the boat thereby altering the distance between the transducer and the bottom (Figure 2-6). The manually digitized bottom locations of each image file along with the X-Y location was converted to a text file as longitude, latitude, and depth. All text files were loaded into Excel by date recorded and the depth of each ping was converted to famsl by using the daily mean water surface recorded by USGS gage 8054500. All data for each date were compiled for import into Esri® ArcMap™ 10.1

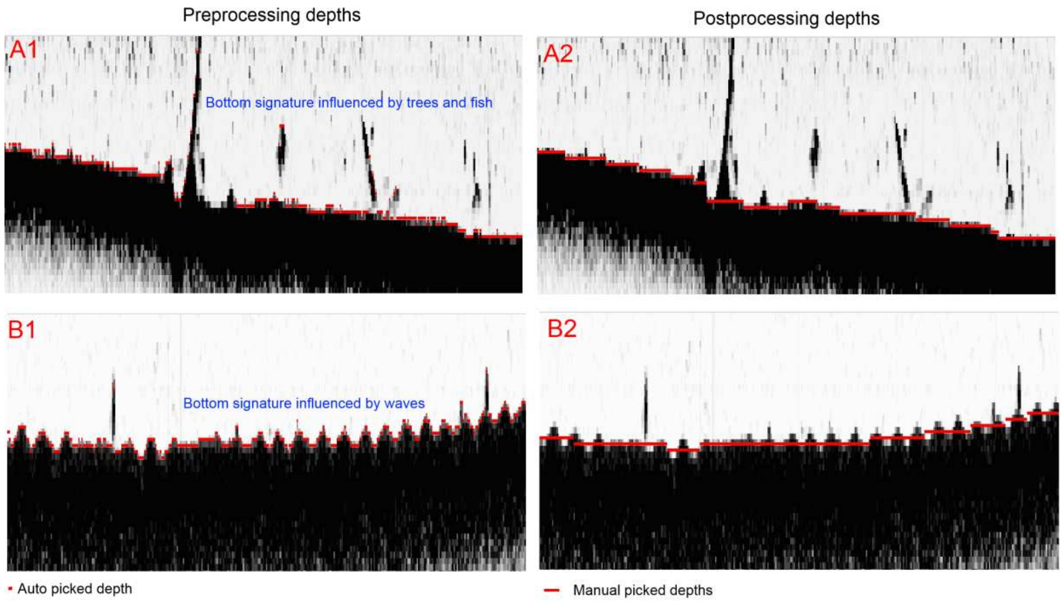


Figure 2-6 Image examples of bathymetry data processing.
Red pixels in all images represent bottom surface depth picks. Images A1 and B1 show positions of software picked depths. Images A2 and B2 show manually picked depths.

2-4.2 Bathymetry Map Contouring

A satellite image courtesy of bing™ was imported into Esri® ArcMap™ 10.1 as a base map of the study area. High resolution orthoimages (0.5 ft/pixel) acquired through the USGS (2013) were overlaid on the base map. The file containing X, Y, and Z data was imported into Esri® ArcMap™ 10.1. Using this software, decimal longitude and latitude were converted from WGS 84 to NAD 83 Texas North Central FIPS 4202 so that all data were in feet. Next, a triangulated irregular network (TIN) was created. The TIN was then converted to a raster using 32-bit floating point output data, linear interpolation, and a sampling cell size of 25 x 25.

The resulting raster was trimmed by a polygon so that only subaqueous connected points connected by the TIN process remained. The trimmed raster was smoothed for improved contour aesthetics using the focal statistics tool. For this, a circular neighborhood radius of 2 cells was used and the mean values were used for each neighborhood circle (Price, 2006). The smoothed raster was used to create various contour intervals for the study area. In all areas of the survey, distance between data points was wider in the basinward direction than perpendicular to flow. In deeper areas of the prodelta, increased distance between data collection paths led to software generated contouring anomalies. In these areas the software was sometimes unable to link contours between rows of data points. This resulted in basinward aligned rows of closed contours and other anomalies (Figure 2-7). Areas where contour closures or other contouring anomalies were obviously related to data point spacing or contouring algorithms were manually corrected to produce the final contour maps.

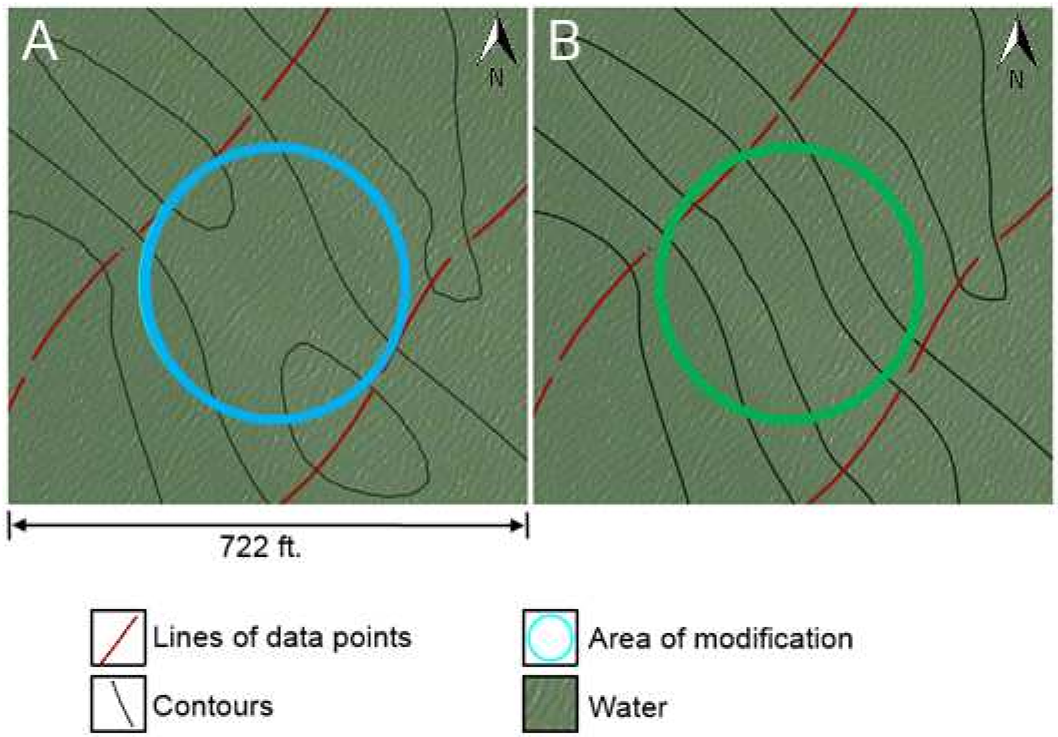


Figure 2-7 Two images showing contour modifications performed in bathymetry mapping. In both images, the basinward or down dip direction is to the southeast. The blue circle in image A indicates an area where contouring software was unable to link contours due to greater data point spacing in the down dip direction. The green circle in image B indicates the same area with manual contour corrections. Map generation: Esri® ArcMap™ 10.1. Image courtesy of USGS © 2013 Microsoft Corporation ImagePatch.com.

2-4.3 Cross Sectional Area and Width Normalization

Channel cross sectional area and channel width normalization was performed using depth data acquired during bottom sampling. All normalizations were produced for the main channel only. There were several chute cutoffs within the study area but all were dry during the study period and were not considered in channel calculations. For mid-channel islands, the channel areas and widths were calculated for the channel on both sides of the island and summed. Bottom sampling was performed over many weeks; during this period the reservoir level and creek level were dropping. In order to normalize the cross sectional areas, a model was created and used to adjust the surface levels of all cross sections so that they all corresponded to an equal elevation. Using this same model widths were adjusted for falling elevations. The elevation of 529.08 famsl was chosen as the reference elevation to adjust all cross sections to, as this was the mean elevation of Grapevine Reservoir on the day the last sets of cross sections were measured. For this model, all slopes (levee or creek bottom) between data points within a cross section were assumed constant. From the measured segment distances and segment depths (Figure 2-8, A), cross sectional area was approximated by triangles and irregular polygons (Figure 2-8, B). The mean depth of the irregular polygons was found (Figure 2-8, B) and resulted in the rectangles shown in (Figure 2-8, C). This simplified the area calculation to segment distance times mean depth. Triangles were used for the area calculation of the end segments to depict a disproportional volume change with a drop in elevation.

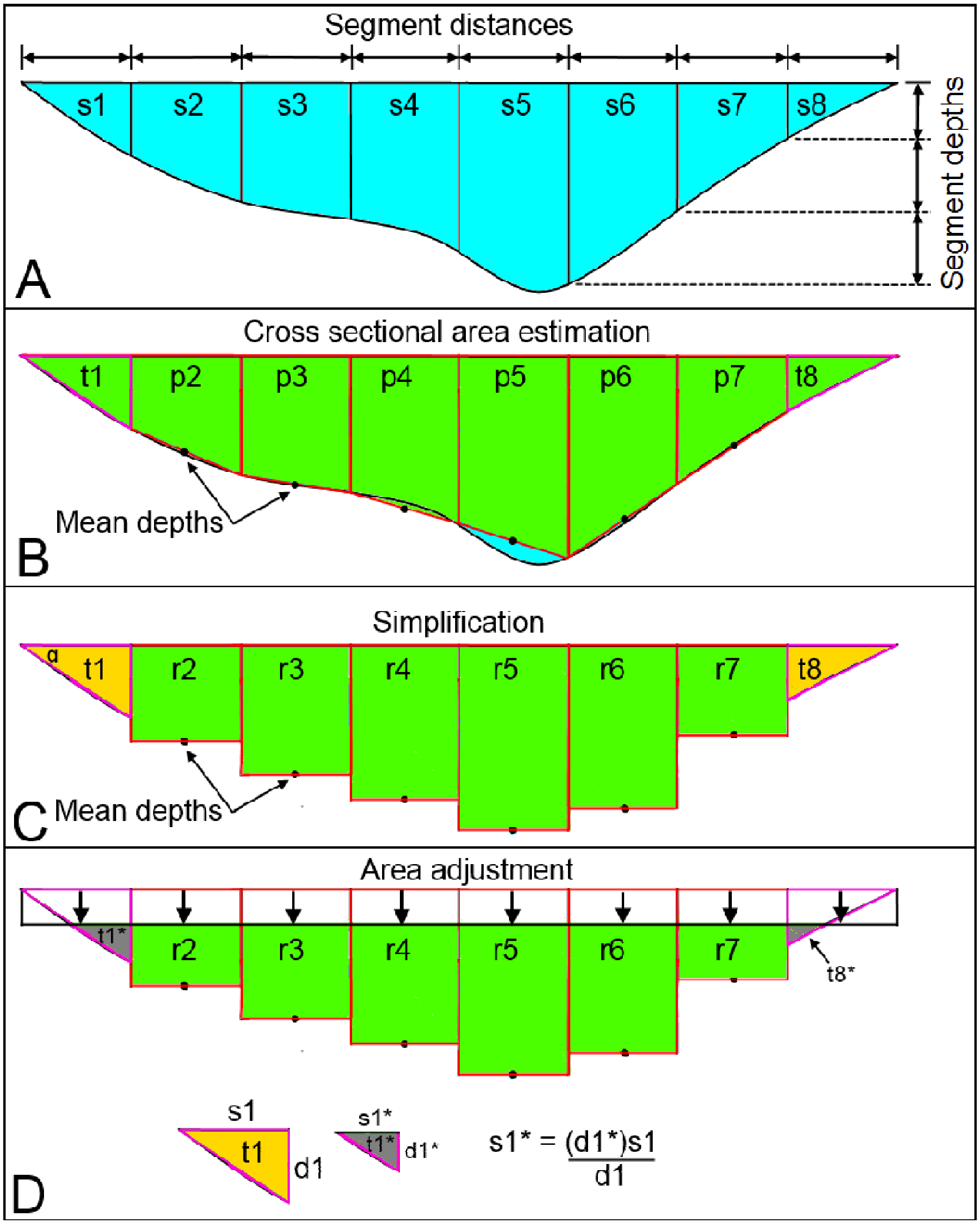


Figure 2-8 Cross sectional area calculation model (steps A-D).
See text for explanation of model use.

For the adjusted cross sectional area calculation at a lower water surface elevation, the depths were adjusted (Figure 2-8, D) to equate for the water surface elevation change, then the area for each rectangle was recalculated. For the triangular end sections, similar triangles were used to find a new segment length. In the example (Figure 2-8, D) a new segment length (s1*) was found using the adjusted depth (d1*) and the original triangle. Lastly, the areas of all adjusted rectangles and triangles were summed for each individual cross section. Some minor error is implicit in this calculation as this did not account for backwater elevation gain in the channel upstream from the point where the channel reached lake level. This approach systematically underestimates the relative area of the downstream cross sections by a minor amount, but was not considered sufficient to influence interpretations and was not corrected.

2-4.4 Bedload Mapping

Sand mapping of Denton Creek was accomplished by importing the locations and the USDA textural soil classification of the 474 bottom samples into Google Earth™ with icons to designate sediment type. The sediment classifications sand, loamy sand, and sandy loam were grouped together. Polygons were drawn linking the spot locations of these grouped classifications.

Chapter 3 Results

This chapter presents maps, graphs and images that are used to analyze the morphology and physical parameters of the Denton Creek Delta. First, data are presented on the modern Denton Creek Channel with respect to bedload, channel parameters, and the relationship of the modern channel to the channel that preexisted reservoir impoundment. Next, data are presented on the growth, composition, and stabilization of the Denton Creek levees. Lastly, bathymetry maps of the prodelta and data related to the advancing mouth are presented.

3-1 Denton Creek

3-1.1 Bedload

A map with polygons connecting subaqueous sandy bottom sediment (sand, loamy sand, and sandy loam) shows that sandy channel bottoms are continuous and follow the inside of meanders in the portion of Denton Creek just west of the Flower Mound boat ramp (Figure 3-1, B). In this area, clays are typically found at thalweg depths and sand deposits begin 1 to 3 ft (0.3 to 0.9 m) above the thalweg and continue toward the inside of the meander bends. Within this area, located about 13,400 ft (427 m) from the mouth of Denton Creek, there are two cross sections circled in blue (Figure 3-1). Observations, cross sectional area calculations, and thalweg depths indicated that the channel is choked by sand in this area. This is evident by the significant decrease in thalweg depth (Figure 3-2) and channel cross sectional area (Figure 3-3) for these two locations when compared with data from neighboring cross sections. In fact, this is the only portion of the study area where large sand accumulations became subaerially exposed during the study (Figure 3-4).

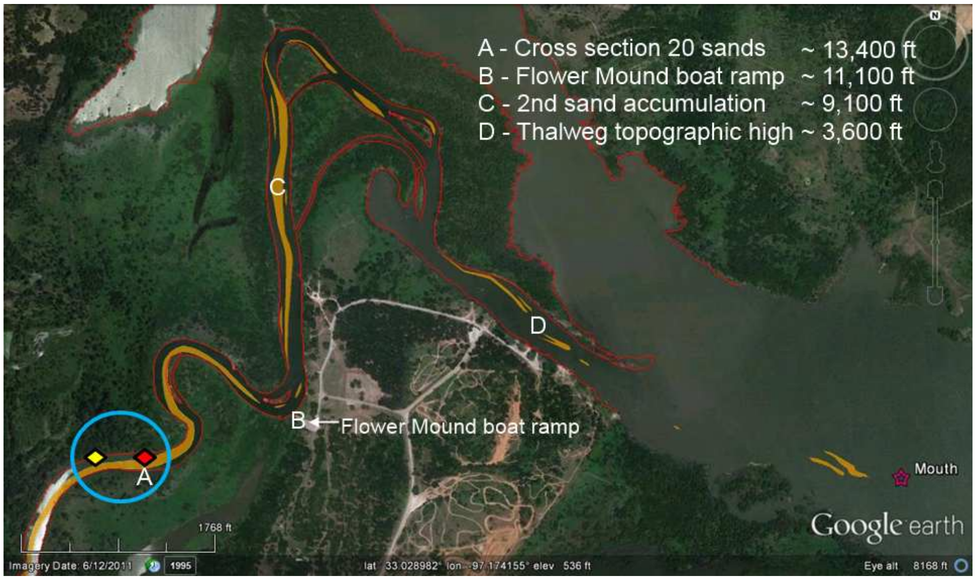


Figure 3-1 Denton Creek sand map.
Sandy sediment (sand, loamy sand, and sandy loam) is indicated by orange polygons. Denton Creek and parts of Grapevine Reservoir are outlined in red. The Denton Creek Delta mouth is indicated by a star. Cross sections 20 and 21 are indicated by red and yellow diamonds, respectively. Approximate distances to points of interest A-D are given as distances from the Denton Creek mouth. Satellite image source: Google Earth™.

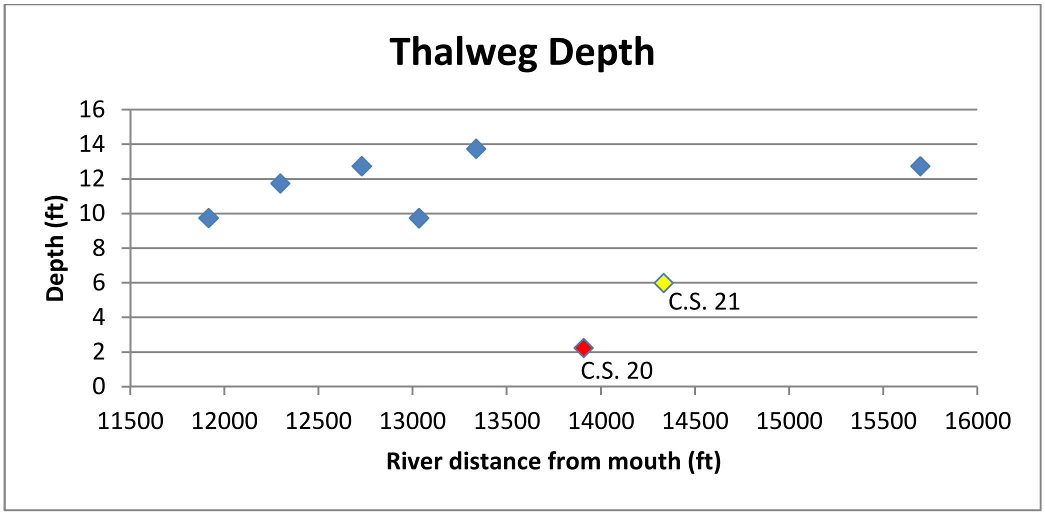


Figure 3-2 Thalweg depth west of the Flower Mound boat ramp.
Positive depth numbers on Y-axis represent feet below 529.08. Cross sections 20 and 21 are indicated by red and yellow diamonds, respectively.

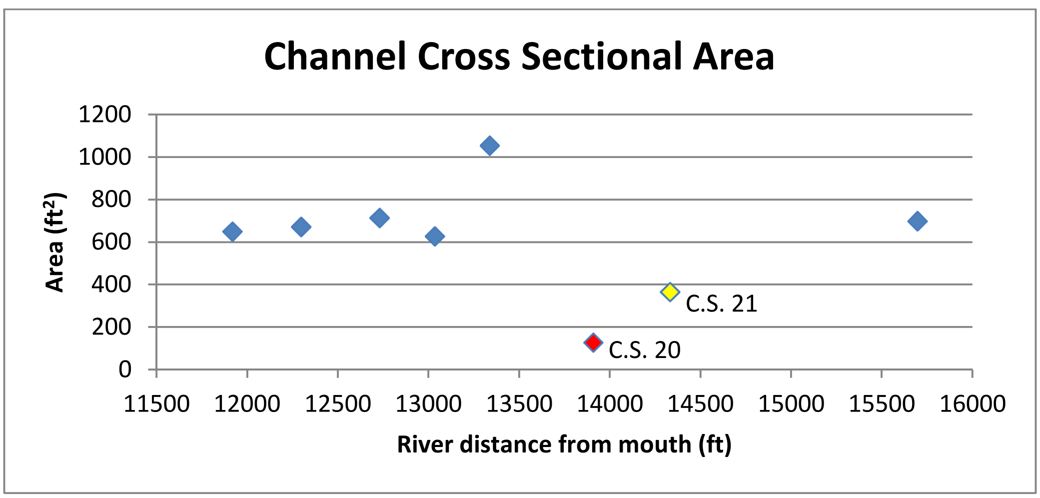


Figure 3-3 Channel cross sectional area (ft^2) west of the Flower Mound boat ramp. Area calculated with respect to a surface elevation of 529.08 famsl. Cross sections 20 and 21 indicated by red and yellow diamonds respectively.

Figure 3-4 Sand accumulation within the channel along cross section 20.

Sandy bottoms were discontinuous near the boat ramp but became continuous again just north of the boat ramp in the long straight section of channel that runs almost due north (Figure 3-1). Limestone bedrock outcropped along areas just north of the boat ramp along the east bank from about 10,700 to 10,900 ft (3,261 to 3,322 m) from the mouth. The limestone extended from the bank no more than 25 ft (7.6 m) into the channel bottom in an area where channel widths average about 200 ft (70 m). Towards the north end of the straightaway at about 9,100 ft (2,774 m) from the mouth was another area with a sand accumulation restricting the creek. However, the data showed a less significant reduction in thalweg depth and channel cross sectional area at this location.

Sandy bottoms became discontinuous again along the tight loop near the north end of the map and remained so the last 7,000 ft (2,134 m) downstream to the mouth. Over this span the bottom was predominately clays and there were two large areas where little or no sandy sediments were found in the last 5,800 ft (1,768 m). One area spanned 2,200 ft (671 m), and extended about 700 to 2,900 ft (213 to 884 m) from the mouth. About 4,800 ft (1,463 m) from the mouth was a second near shore outcrop of limestone. This limestone outcrop extended from the bank less than 10 ft (3 m) into the channel bottom where the channel width was about 120 ft (37m). Approaching the mouth there was a noticeable increase in sandy deposits but these were mostly small thin discontinuous deposits.

Due to low reservoir conditions, cross section bottom sampling of the last 210 ft (64 m). of channel was not achieved. Two individual gouge cores were acquired from the channel at locations about 90 ft (27 m) and 135 ft (41 m) upstream of the mouth (Figure 2-5). These two cores were each sampled to a depth of 3.3 ft (1 m). Samples from both cores were predominately (>90%) clay and contained no sandy intervals.

3-1.2 Thalweg Depths and Channel Cross Sectional Areas

Thalweg depths and channel cross sectional areas were calculated from depths acquired in bottom sampling cross sections and normalized to a reservoir surface elevation of 529.08 famsl (161.26 mamsl) (Figure 3-5). These data show that Denton Creek is far deeper and has a larger cross sectional area west of the Flower Mound boat ramp than in any area downstream. The area west of the ramp was defined as being about 11,100 to 15,700 ft (3,383 to 4,785 m) from the mouth of Denton Creek and is indicated by the blue zone in the figure. Except for the area previously discussed where the channel is plugged with sand, cross sectional areas over this interval ranged from 600 to 1,100 ft^2 (55.7 to 102.2 m^2) and thalweg depths were over 8 ft (2.4 m).

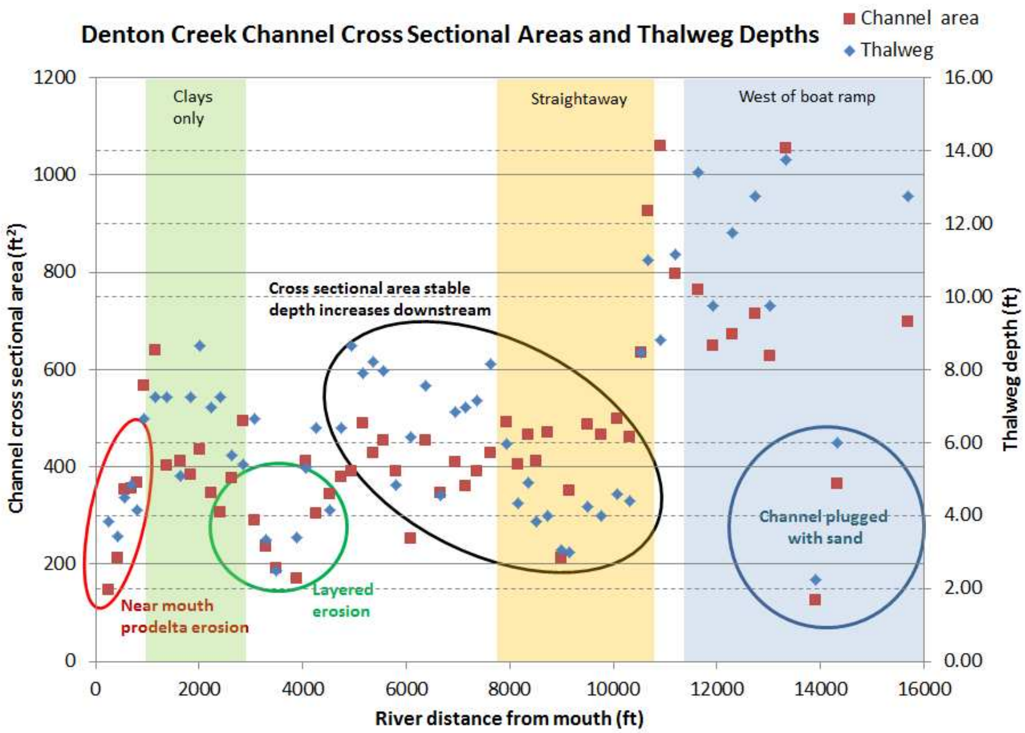


Figure 3-5 Denton Creek cross sectional areas and thalweg depths. Cross sectional areas are represented by red squares and the values are given on the left vertical axis. Thalweg depths are represented by blue diamonds and the values are given on the right vertical axis. Major grid lines are solid for the left vertical axis and dashed for the right vertical axis. Distances from the mouth are on the x-axis. Areas of interest pertaining to Figure 3-1 and discussed within the text are indicated by green, orange, and blue colored zones. Data patterns and anomalies described in the text are indicated by circles or ovals.

Following an abrupt change in cross sectional area and thalweg depth just north of the boat ramp, the majority of the straightaway north of the boat ramp consisted of stable cross sectional areas and thalweg depths. The straightaway is indicated by green in the figure and covered an interval from about 7,800 to 10,700 ft (2,377 to 3,261 m) from the mouth. Over the majority of the straightaway, cross sectional areas were fairly consistent and were generally between 400 to 500 ft^2 (37 to 46 m^2) and thalweg depths ranged between 4 and 5 ft (1.2 to 1.5 m). At 8,990 ft (2,740 m) from the mouth there was a noticeable decrease in depth and channel area. This area contained the largest accumulations of sand within the straightaway. Overall, the cross sectional area was fairly consistent over the straightaway and this trend continued about 2,800 ft (853 m) downstream of the straightaway (Figure 3-5, black oval). Over this same area, the channel width narrowed and deepened in a downstream direction.

From a distance of about 4,900 to 3,600 ft (1,494 to 1,097 m) both cross sectional area and depth decreased rapidly. At about 3,600 ft (1,097 m) from the mouth, cross sectional area and depth reached minimum values of 171.5 ft^2 and 2.5 ft (15.9 m^2 and 0.76 m), respectively. Over this interval, examination of the 2007 orthoimages revealed a significant reduction in channel dimensions when compared with measurements of areas upstream or downstream (Figure 3-6). Additionally, photographs taken of this area during the low water conditions of the study showed that the area (Figure 3-5, green circle) had recently undergone layer by layer erosion of exposed prodelta clays and/or levee deposits (Figure 3-7), widening the channel in this area.

Figure 3-6 Channel restriction approximately 3,600 ft from the mouth of Denton Creek. Orthoimage source: USGS Earth Explorer, NCTCOG.

Figure 3-7 Layered erosion, approximately 3,600 ft from the mouth of Denton Creek. View direction is to the southeast, across the area indicated by a square in Figure 3-6.

From the minimum channel dimensions at a distance of 3,600 ft (1097 m) from the mouth, the channel area and thalweg depth both increased in the downstream direction to about 1,200 ft (366 m) from the mouth. Over this distance the bottom was dominantly comprised of clays and the bottom was extremely rough. During bottom sampling, abrupt changes were observed in channel bottom elevation. When progressing across the channel perpendicular to flow, elevations rose or fell up to 1 foot over distances less than a foot. These changes in elevation appeared to be linearly continuous, with their long axis parallel to the channel axis. Often, topographic channel bottom lows were filled with soft, highly saturated clays and sometimes contained hardened clay nodules, while topographic channel bottom highs always consisted of relatively hardened and dewatered clays. This roughness, or change in bottom elevation observed during bottom sampling was typically obscured by water turbidity in most locations but was apparent near shore in a few locations (Figure 3-8). Examination of the photograph shows three linear areas (parallel to flow direction) of nodular hardened clays, one of which was subaqueous. Between each of these areas the local topographic lows were filled with soft highly saturated clays. Above the waterline, this can be recognized in the photograph by a smoothed appearance tapering gradually from the uppermost hardened clays to the waterline (Figure 3-8).

Over the final 1,200 ft (366 m) of channel, both channel cross sectional area and thalweg depth decreased (Figure 3-5). The channel bottom remained rough over most of this area. The deeper central portion of the channel was comprised of clays and was flanked by sandy sediment near the channel margins. Channel cross sections ended about 210 ft (64 m) from the mouth, but as previously mentioned, gouge cores revealed that in the deepest portions of the channel at distances of 90 and 135 ft (27.4 and 41.1 m) the channel consisted of clays.

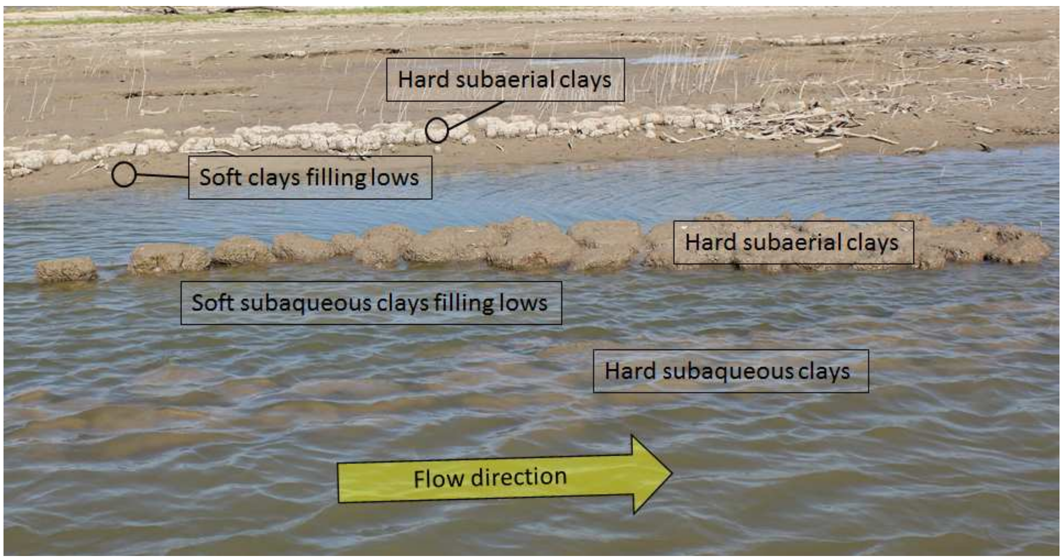


Figure 3-8 Channel bottom roughness example.
This photograph is a northern view of Denton Creek approximately 1,000 ft from the mouth. The image shows that rows of hardened dewatered clays exist parallel to the flow direction on the northern levee, subaerially within the channel, and subaqueously within the channel. These areas of hardened clays alternate with areas where the clays have been eroded and the resulting topographic lows contain soft highly liquid clays.

3-1.3 Channel Width

Channel widths were calculated from bottom sampling data acquired in 2012 and were compared with map measured widths from the 2007 high resolution orthoimages (Figure 3-9) to look for short term changes in channel dimensions. Overall flooded channel widths were greater for the 2012 data, but that was to be expected, as the reservoir was higher in 2012 than in 2007 by 5.25 ft (1.6 m). However, it was expected that the difference in elevation between the two would be similar for all distances. Indeed, the difference in channel widths was very similar from 16,000 to 5,000 ft (4,877 to 1,534 m) from the mouth. In contrast, from about 4,000 to 1,500 ft (1,219 to 457 m) the 2012 widths were about double that of the 2007 widths. Most of this difference is likely a result of a shallower channel profile particularly at the margins of the channel. However, it was observed that these areas of shallower margins showed evidence of recent erosion (Figure 3-7). Similar to thalweg depth and cross sectional areas discussed previously, channel width for both data sets showed a linear decrease over the last 1,000 ft (305 m) of channel toward the mouth. Additionally, the current condition of the channel over the last 1,000 ft (305 m) must be similar to the channel in 2007, as both a reduction in width and depth is seen in the 2007 high resolution orthoimages (Figure 3-10).

Reservoir levels dropped during the study period exposing standing pre-impoundment tree stumps. Based on pre-impoundment channel locations (see section 3-1.4) these trees had once either topped pre-impoundment levees or grew just outside the levees on the floodplain. The tree stumps provided insight into depths and widths of erosion relative to the preexisting channel location. Areas west of the boat ramp contained few trees stumps between the channel levees and these were within a foot or two from the levees. In contrast, from the Flower Mound boat ramp north along the straightaway, many trees stumps occupied the channel and at times were near the centerline (Figure 3-11). Pre-impoundment tree stumps within the channel are indicated by white arrows.

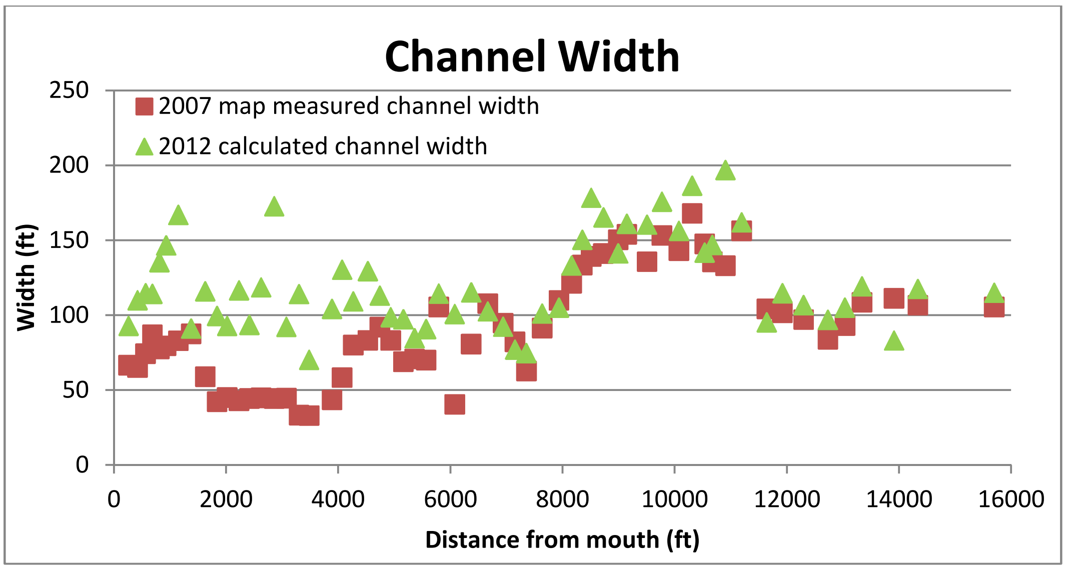


Figure 3-9 Denton Creek Channel widths.
2012 calculated channel widths are represented by green triangles, and 2007 image measured channel widths are represented by red squares. Thalweg distances from the mouth are on the x-axis.

Downstream, approximately 4,000 ft (1,219 m) from the mouth, stumps of pre-impoundment trees were nearer the margins of the channel (Figure 3-12). Additionally, trees stumps still in place were often catch points for fallen timber and created debris piles in areas. One such debris pile is indicated by the yellow arrow.

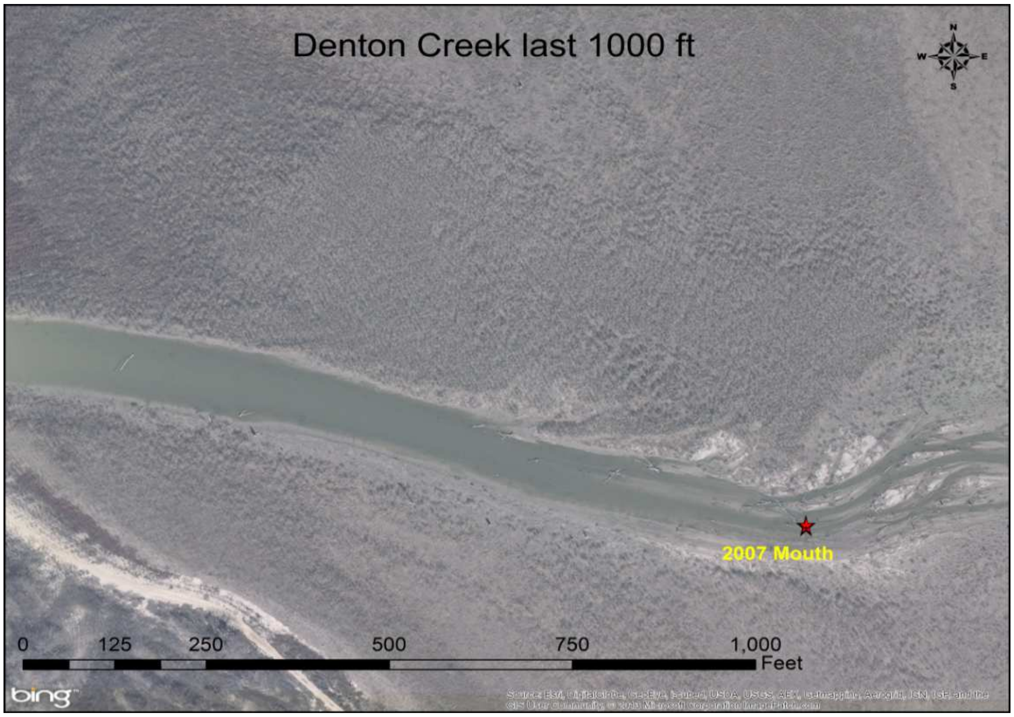


Figure 3-10 Denton Creek Channel width reduction over the last 1,000 ft.
Map generation: Esri® ArcMap™ 10.1. Aerial photograph: USGS Earth Explorer.

Figure 3-11 Pre-impoundment tree stumps along the straightaway.
View is to the north (downstream) and taken just north of the Flower Mound boat ramp. White arrows indicate pre-impoundment tree stumps that existed on or near the pre-impoundment levees. Pink arrows indicate areas of channel widening.

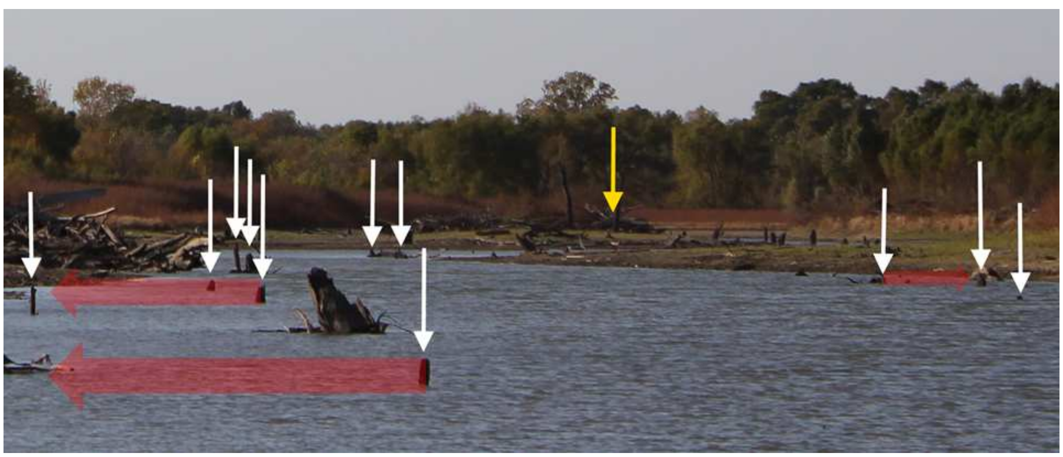


Figure 3-12 Pre-impoundment tree stumps and debris piles.
View is upstream to the northwest and taken about 4,000 ft from the Denton Creek mouth. The white arrows indicate pre-impoundment tree stumps that existed on or near the pre-impoundment levees. The yellow arrow indicates and area where standing timber has created a log jam. Pink arrows indicate areas of channel widening.

3-1.4 Historic Delta Progradation

A historic aerial photograph taken on January 4, 1952 was acquired through the USGS (USGS, 2013). The photograph reveals the Denton Creek Channel before reservoir impoundment. The channel was digitized using Esri® ArcMap™ 10.1 for the purpose of evaluating original channel position relative to advancing channel position through time (Figure 3-13). A post-impoundment series of maps (Figure 3-14) showed that the Denton Creek Channel and Delta have followed the channel trend that predated impoundment with little deviance.

Examination of the 1968 aerial photograph reveals remnants of tree covered pre-impoundment levees in the northeast corner and the absence of a levee bound channel on the west side of the straightaway.

In the 1982 image the elevation of Grapevine Reservoir is 3.55 ft (1.08 m) lower than it was in the 1968 image. Some of the apparent delta growth in the 1982 image is likely due to the lower elevation. However, the major areas of growth appear to be along the west edge of the straightaway and near the preexisting chute cutoff on the east edge of the straightaway.

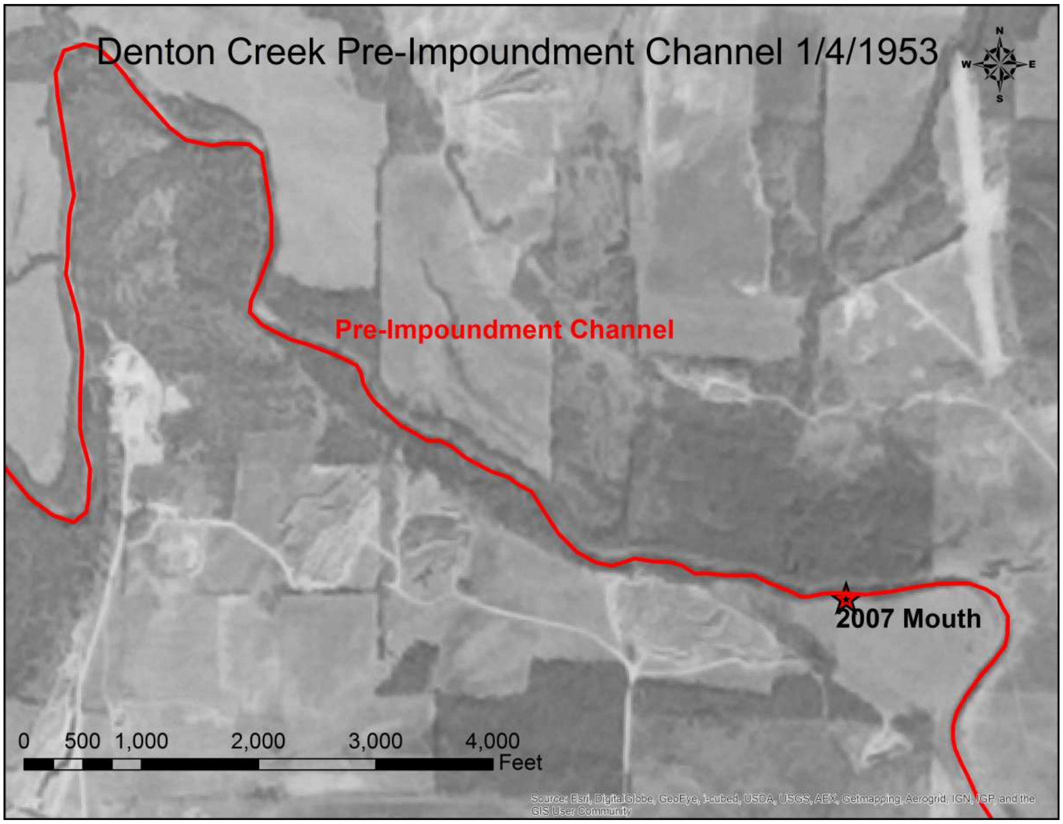


Figure 3-13 Aerial photograph of the 1953 Denton Creek Channel. Channel is indicated by a red line. Map generation: Esri® ArcMap™ 10.1. Aerial photograph: USGS Earth Explorer.

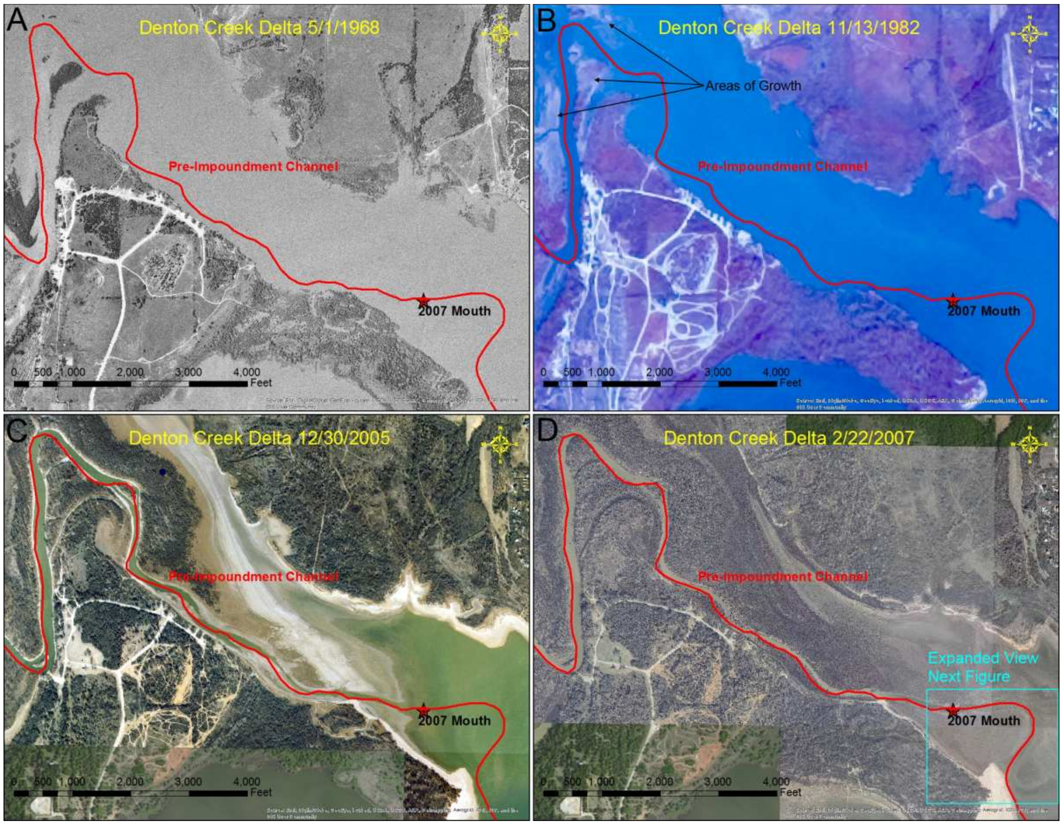


Figure 3-14 Pre-impoundment channel adherence.
All images are of the Denton Creek Delta. Image A: 1968 aerial photograph, reservoir surface elevation 536.25 famsl. Image B: 1982 aerial photograph, reservoir surface elevation 532.9 famsl. In Image B, arrows indicate areas of growth between 1968 and 1982. Image C: composite of several 2005 photographs; reservoir elevation 528.39 famsl. Image D: composite of several 2007 aerial photographs, reservoir surface elevation 523.83 famsl. The blue box represents the area of expanded view in Figure 3-15. The red line represents pre-impoundment channel digitized from Figure 3-13. Map generation: Esri® ArcMap™ 10.1. Aerial photographs: USGS Earth Explorer.

In the 2005 image the elevation of Grapevine Reservoir is 4.41 ft (1.34 m) lower than it was in the 1982 image. This exposed more of the delta, and allowed for further comparison of the 2005 channel with the pre-impoundment channel. There is little deviation of the 2005 channel from the pre-impoundment channel. Small deviations may result from statistical errors from geo-referencing the 1952 photograph as well as digitization of the low resolution image. As before, due to the decrease in elevation between the two photographs, actual delta growth is less than apparent growth. Therefore, measurement of increased subaerial sediment would not accurately depict delta growth. However, the advancement of trees lakeward down the advancing delta is a good indicator of growth, because tree establishment would require the delta to remain subaerial for the majority of the year. Based on tree advancement, the levee along the west edge of the straightaway advanced 1,300 ft (396 m) and encompassed the island in the far north end of the 1982 image. Tree advancement also shows that the delta (through growth of the northern levee) became established an additional 4,200 ft (1,280 m) basinward between 1982 and 2005.

Remarkably, comparison of the pre-impoundment channel with the 2007 prodelta exposure reveals that the meander depression in the prodelta clays directly corresponds to the location of the pre-impoundment channel (Figure 3-15). In this image the prodelta depression is visible as a dark meander in the prodelta with an apparent smooth texture.

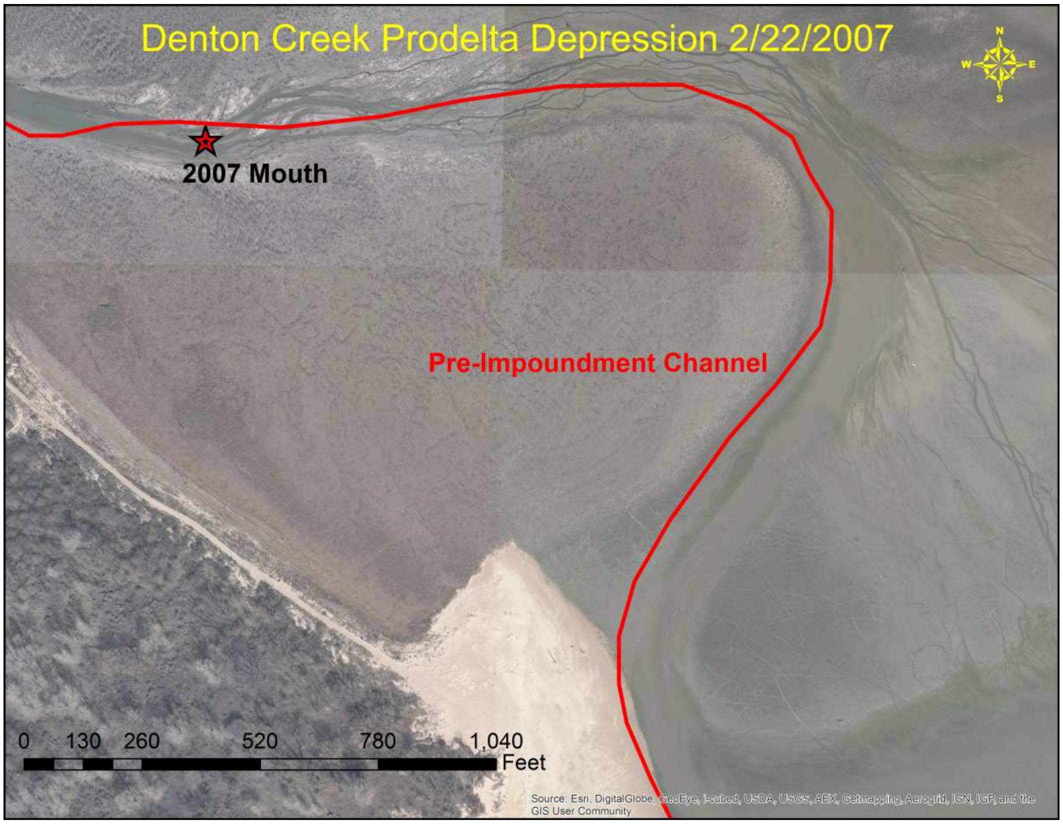


Figure 3-15 Denton Creek prodelta depression and pre-impoundment channel. This 2007 high resolution orthoimage shows the adherence of the depression in the modern prodelta to the pre-impoundment channel (red line). Map generation: Esri® ArcMap™ 10.1. Aerial photographs: USGS Earth Explorer.

3-2 Levees

3-2.1 Levee Growth

One component of channel and delta advancement is levee growth. Levees can be defined as subaerial or subaqueous, but their growth always occurs subaqueously. Whether they are defined as subaerial or subaqueous is dependent upon the water elevation within the basin and therefore their designation as subaerial or subaqueous has a temporal aspect. Grapevine Reservoir, like other small basins, experiences large fluctuations in surface elevation. The normal pool level of Grapevine Reservoir is 535.00 famsl (136.07 mamsl) (Austin, et al., 2002) (Solis, et al., 2011). This elevation is higher than the post fill-up mean and median reservoir levels of 533.18 and 533.30 famsl, respectively. To analyze delta and levee growth, available satellite images were cross-referenced with reservoir elevations in order to find a set of images acquired at comparable reservoir elevations over the longest time spans possible. Three images were selected to evaluate levee growth. These images were acquired at slightly less than normal pool and provided a good basis for evaluating the two dimensional growth of the delta/levee. Lake levels on the days these images were acquired only varied 0.12 ft (0.036 m) between the three images (Table 1). Reported growth in the 2005 and 2011 images is an overestimate due to the lower reservoir levels in these images, but the overestimate is negligible.

Currently the Denton Creek Delta has one dominant levee on the north side of the channel. The stature of second levee is minimal, it is essentially deposited along the shore, where it has filled in shoreline irregularities and filled, partially filled, or extended some preexisting shoot cutoffs. Between 1995 and 2005 the delta grew approximately 71 acres

(29 ha) or 6.9 acres per year (2.8 ha/yr) (Figure 3-16) (Table 1). Most of this growth extended the levee basinward, although some of the growth was by splays or overbank sedimentation infilling some of the far western portion of the reservoir and increasing the levee's width in the far northern area. During this time period, the northern levee grew basinward about 2,500 ft (762 m) and over the majority of this length the levee was 500 to 800 ft (152 to 244 m) wide. Nearly the entire levee and delta that was established prior to 2005 is now tree covered.

Table 1 Denton Creek Delta Growth.
Table lists increases in subaerial delta surface area growth for 2 successive images. 2005 numbers are based on changes in subaerial exposure between 1995 and 2005 images. 2011 numbers are based on changes in subaerial exposure between 2005 and 2011 images. Reported growths are based on polygons representing changes in subaerial exposure using tools in Google Earth Pro.

Image Date	Image Source	Elev. (famsl)	Subaerial Growth (ft^2)	Subaerial Growth (ac)	Mean Growth (ac/yr)	Average Discharge (ft^3/s)
1/30/1995	Google Earth Pro 7.0.3.8542, USGS	534.87	Baseline	Baseline	Baseline	N/A
5/17/2005	Google Earth Pro 7.0.3.8542, © 2013 DigitalGlobe	534.85	3.1×10^6	71.26	6.9	100.2
6/12/2011	Google Earth Pro 7.0.3.8542, USGS	534.75	621,490	14.27	2.4	77.2
Totals			3.7×10^6	85.53	5.2	91.7

Between 2005 and 2011 the delta grew an additional 14.3 acres (5.79 ha) and extended the length of the northern levee by another 800 ft (244 m) (Figure 3-16). The growth during this interval was divided between the northern levee and infilling in the northwest corner. Very little of the delta or levee growth that occurred between 2005 and 2011 appeared to have tree coverage, based on the 2011 image.

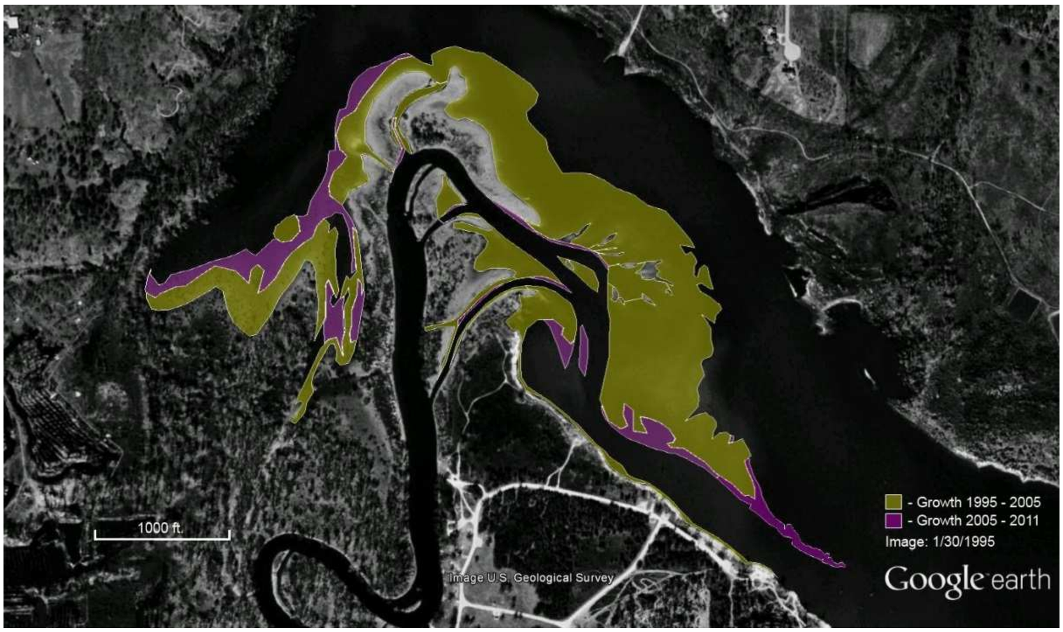


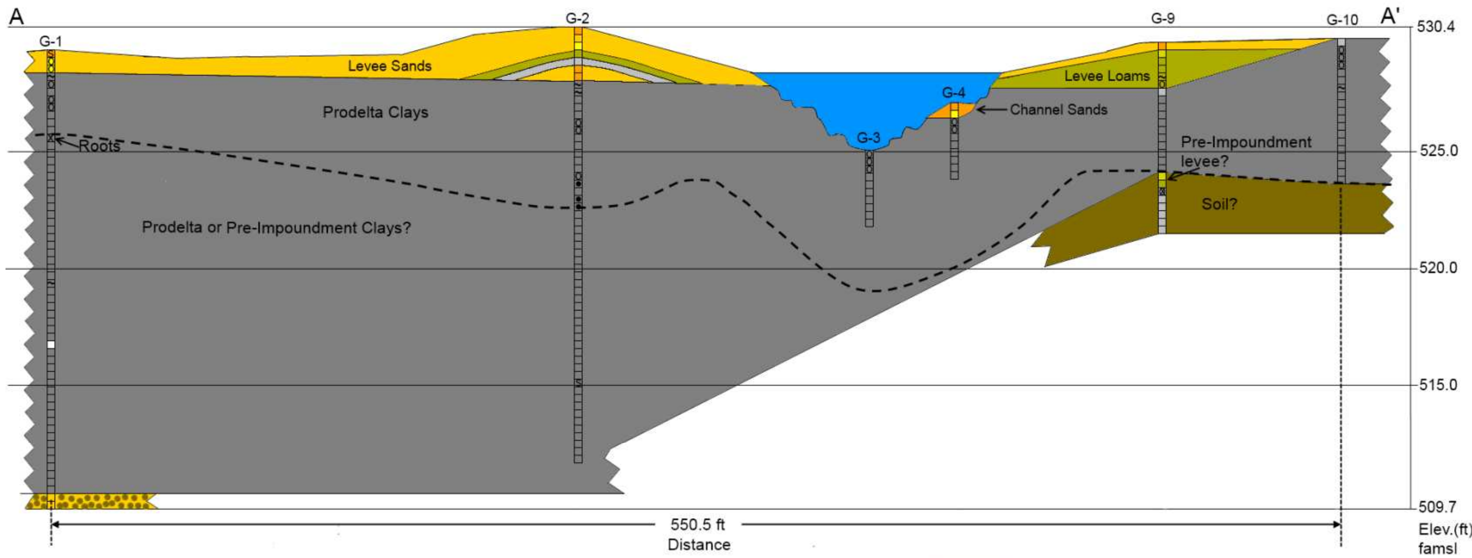
Figure 3-16 Denton Creek subaerial delta and levee expansion.
Image shows the 1995 subaerial extent of Denton Creek Delta. Yellow polygon indicates subaerial surface area growth from 1995 to 2005 as digitized from a 2005 image. Purple polygon indicates subaerial surface area growth from 2005 to 2011 as digitized from a 2011 image. Satellite image source: Google Earth™, USGS 1995

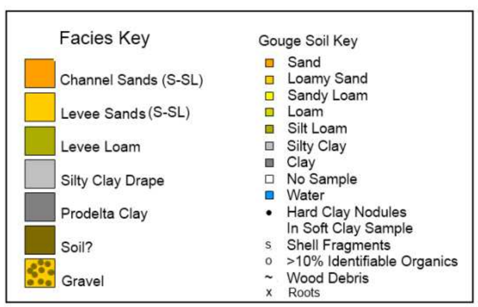
Growth rates varied considerably over the two intervals. Between 2005 and 2011 the growth rate averaged 4.5 acres per year (1.8 ha/yr) less than it did between 1995 and 2005. This was likely due to a lower average discharge of Denton Creek between 2005 and 2007 and fewer large events (Figure 2-4).

3-2.2 Levee Composition

Levee composition was evaluated by the analysis of six gouge cores taken across the Denton Creek levees and channel (Figure 3-17, insert). The location of this cross section is about 500 ft (152 m) upstream of the mouth identified in the 2007 orthoimages. At normal or mean reservoir levels the levees would be subaqueous at this distance from the mouth, but at the time the gouge cores were sampled four of the six locations were subaerial.

Facies given in the cross section were based on similar depositional regimes (Figure 3-17). The cross section showed that the upper portion of the northern levee was dominantly comprised of sediment ranging from sand to sandy loam for a thickness of over two feet. This is in stark contrast to the approximately 17 ft (5.3 m) of prodelta and pre-impoundment floodplain clay beneath this levee. The upper portion of the northern levee clays contained leaf and woody debris but visible organics diminished with core depth. Of note, the upper portion of the clay sampled in gouge core #2 was soft and sometimes contained hard clay nodules. Similar to the northern levee, the southern levee was topped with sandy and loamy deposits overriding prodelta clay.





DATA POINTS

Gouge	Lat	Lon
G-1	33.02573	-97.16334
G-2	33.02502	-97.16376
G-3	33.02478	-97.16396
G-4	33.02468	-97.16397
G-9	33.02444	-97.16398
G-10	33.02421	-97.16418

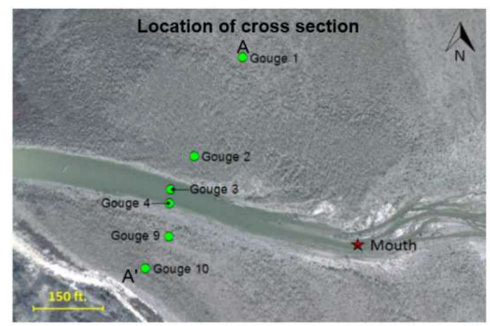


Figure 3-17 Levee cross section, facies key, gouge data locations, and map depicting cross section orientation. The cross section (top) is oriented from A to A', and the position of the gouge locations are indicated in the aerial photograph in the lower right. Color codes for facies used in the cross section as well as a soil sample key pertaining to the gouges is located lower left. Bottom center is a chart showing the latitude and longitude of gouge locations displayed in the cross section.

The channel was cut into the prodelta and is depicted in the cross section as having a highly irregular clay bottom representative of the channel bottom throughout this stretch of channel.

A view looking upstream from the location of gouge #1 on the northern levee reveals the pattern of sand deposited during the last large flow event (Figure 3-18). In this photograph, Denton Creek is on the left and Grapevine Reservoir is on the right. The sand deposit gradually tapered toward the creek in the distance, creating a V-pattern with the apex of the V situated in the upstream direction. This photograph provides additional insight into the process of levee formation.

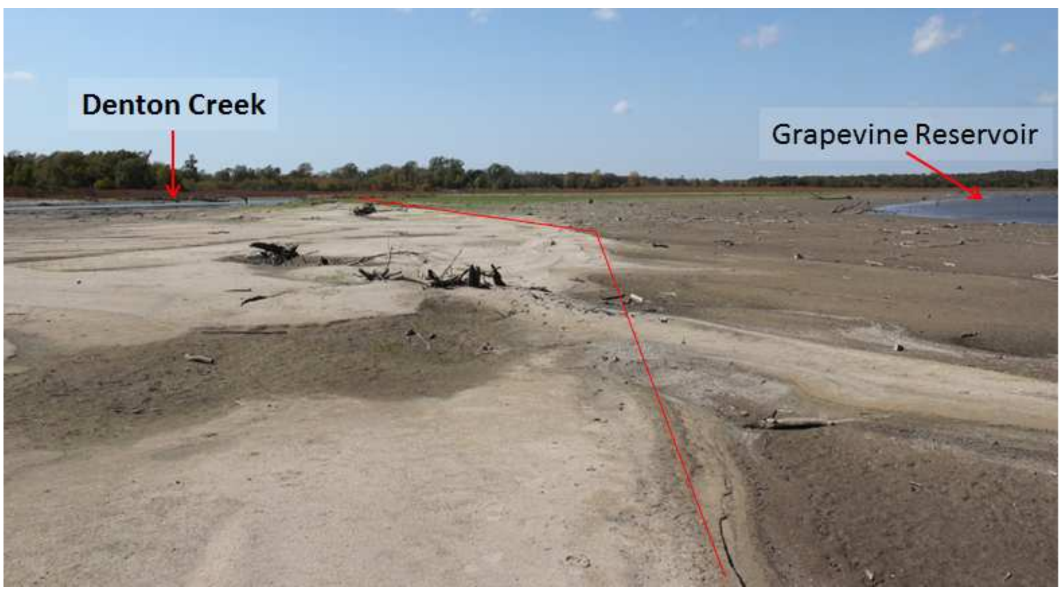


Figure 3-18 Northern levee sand deposit.
View is of northern levee looking upstream along the levee from gouge location G-1 in Figure 3-17. The extent of the sand deposit is indicated by the red line.

Photographic evidence from further upstream demonstrates how successive levee deposits contain less clay and more sand vertically (Figure 3-19). The photograph shows the typical facies observed in the levees, progressing from prodelta clays at the base, to clays or loams with woody debris, to loams or loamy sands, and finally to sands at the top.

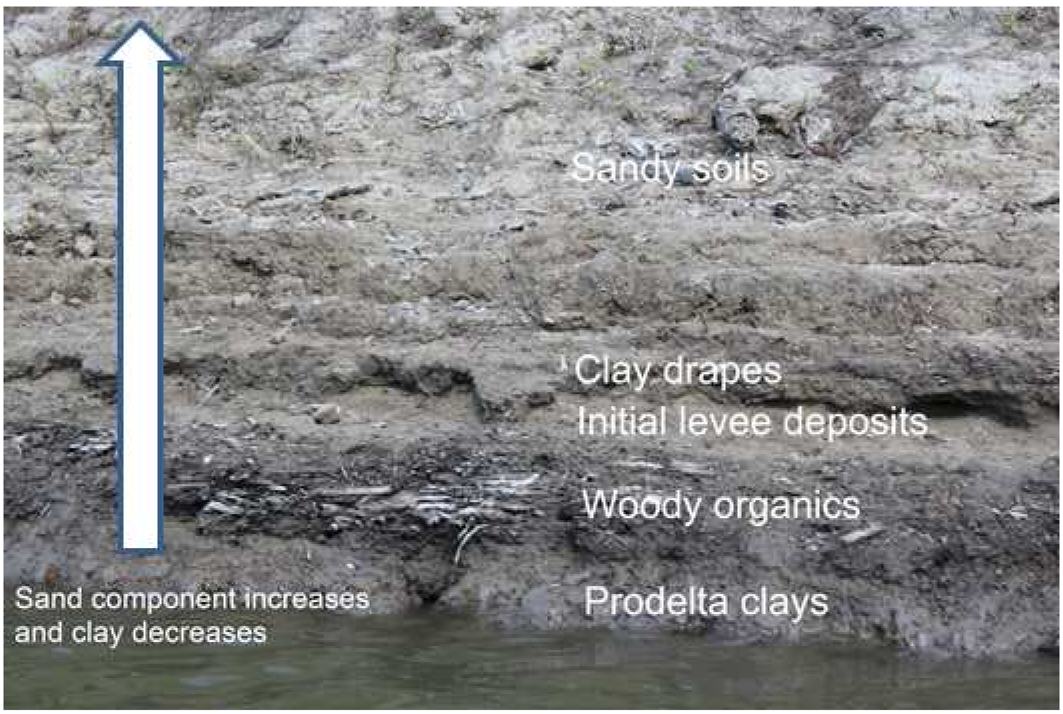


Figure 3-19 Typical progression of levee facies.
Image is of the northern levee about 5,000 ft upstream of the mouth. Arrow shows direction of decreasing clay and increasing sand components.

3-2.3 Levee Stabilization

Large trees and other wood debris often become lodged on emergent subaqueous levees during flow events (Figure 3-20, A). Over time, these deposits are buried and become a part of the levee base and may increase stability. Progressing from the mouth of Denton Creek upstream this burial process was highly evident as woody debris protruded from the levee at various levee heights and either marked the transition from clays to sandier sediment or was contained within the sandier portion (Figure 3-20, B-D).

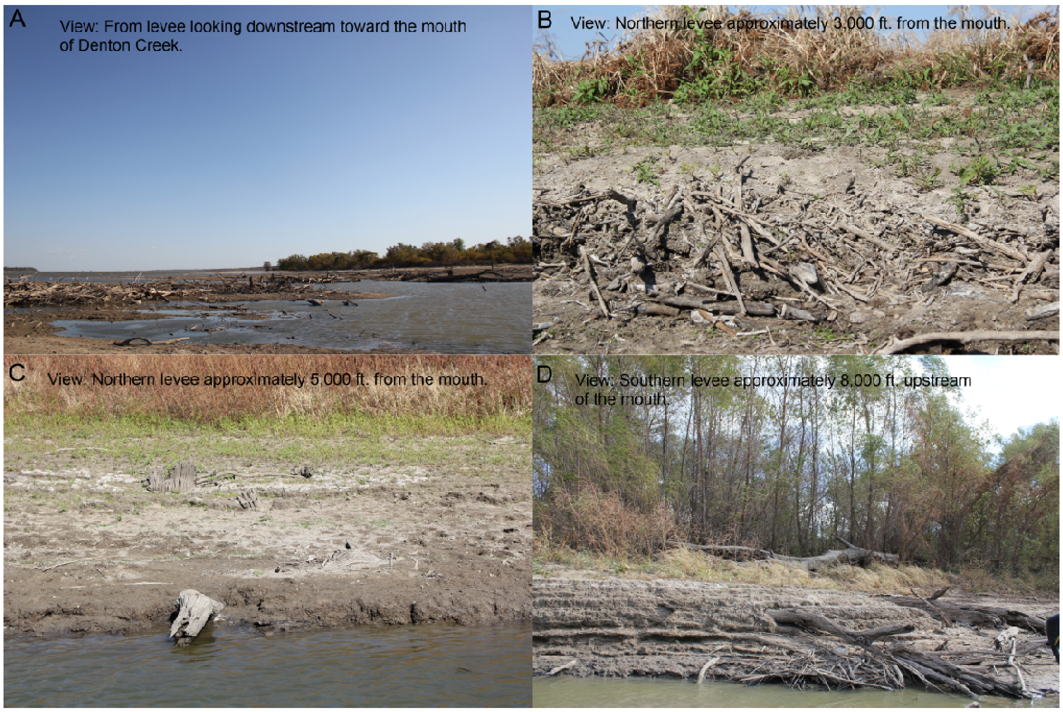


Figure 3-20 Wood debris on and within the levees (images A-D). Image A shows woody debris trapped on the emerging levee. Images B-D show buried woody debris at the base of the levee. Image D also shows woody debris contained within the upper sandier portions of the levee.

Another aspect of levee stabilization comes from the establishment of vegetation and root growth (Edmonds & Slingerland, 2010). As previously mentioned, levee/delta growth that occurred prior to 2005 is already covered in trees. More recent deposits are covered in grasses, tall weeds, and saplings. In fact, throughout the delta, a succession of speciation was evident that progressed from grasses, to tall weeds, to willow trees, and sometimes to cottonwood trees (Figure 3-21). This can be seen in other photos (Figure 3-7) and satellite images as well (Figure 2-2). This series of speciation is presumably based on plant tolerance for wet soils and is therefore presumed to be related to levee height.

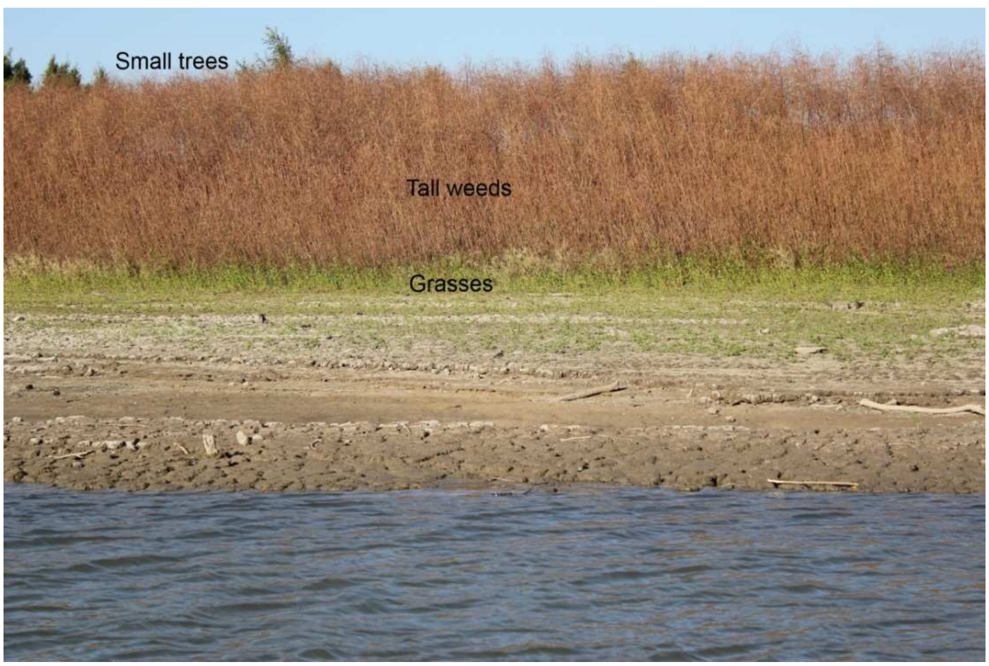


Figure 3-21 Progression of levee vegetation approximately 4,500 ft from mouth.

3-3 Prodelta

3-3.1 Prodelta Bathymetry

Two maps were generated based on data collected during bathymetry sampling. The first map shows a detailed view of the Denton

Creek prodelta with a contour interval of 0.1 ft (Figure 3-22). Overall there was very little bottom variation of the prodelta shown by this map. At areas closest to the mouth, contours flexed in a down dip direction, indicating a gently tapering “turtle-back” shape of the prodelta, perpendicular to the flow direction. This tapering slowly diminished in the down dip direction and the prodelta approached horizontal at the 523.5 ft contour. The down dip slope of the prodelta appeared constant based on the contours and was calculated at 0.0017 between the 525.5 and 520.0 ft contours.

The map also contains the 2007 orthoimages as overlays (Figure 3-22). These images display features that were subaqueous at the time of bathymetric data collection and were found to be in very good agreement with generated contours. The waterline in the 2007 image and individual data points from the bathymetry data were used to find vertical prodelta growth at the location of the waterline. Vertical growth between February 2007 and December 2012 at this location was between 0.7 and 0.8 ft (0.21 to 0.24 m) for all data points sampled.

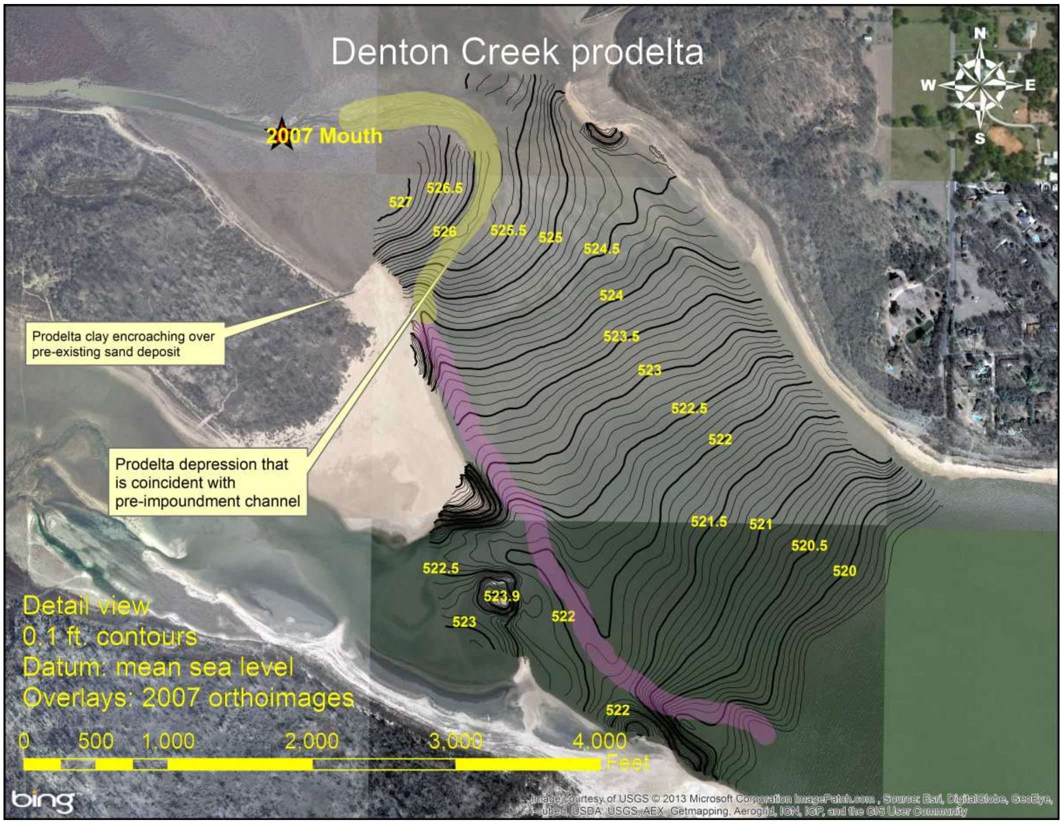


Figure 3-22 Detailed bathymetry map of the Denton Creek prodelta.
The bathymetry map is contoured at 0.1 ft intervals. The mouth of Denton Creek is indicated by the star. The prodelta depression visible in the 2007 images that corresponds to the pre-impoundment channel is highlighted in yellow. The area where the pre-impoundment channel was subaqueous in the 2007 images is highlighted in pink. Map generation: Esri® ArcMap™ 10.1. Background image: USGS © 2013 Microsoft Corporation ImagePatch.com. Overlays: USGS Earth Explorer, NCTCOG

The visible depression in the prodelta was coincident with the pre-impoundment channel in the 2007 orthoimages (Figure 3-14, D) and has been highlighted in yellow on the Denton Creek prodelta bathymetry map (Figure 3-22). The depression is easily recognized by the widening of the gap between the 525.7 and 525.8 ft contours and is annotated on the map. Based on the upward flexure of the 0.1 ft contours progressing down dip along the depression meander, it appears that the depression is very slight and only 0.1 to 0.2 ft (0.03 to 0.06 m) deep. The upward flexure of contours continues basinward along the large sand deposit located in the center of the map. This low area corresponds to the pre-existing channel which is highlighted in pink. Additionally, the 2007 orthoimages reveal how the prodelta clays have prograded over sands that preexisted impoundment.

The second bathymetry map shows the extent of the mappable area based on the data set and is contoured at 1.0 ft intervals (Figure 3-23). Based on this map, the Denton Creek prodelta appears to have almost completely filled in pre-impoundment topography to at least the 520 ft contour. Down dip, between the 520 and 517 ft contours is a transitional area in which the prodelta has filled in the majority of preexisting topographic lows. Progressing further down dip over this area, pre-existing topographic lows become increasingly apparent. By the 516 ft contour, a clearly defined topographic low is visible. This low has been interpreted as the pre-impoundment channel and can be traced basinward to the extent of the map. Even though this area is clearly defined by contours at locations near the end of the mapping area, echo location images show that topographic lows of the channel are partially filled with fine sediment (Figure 3-24).

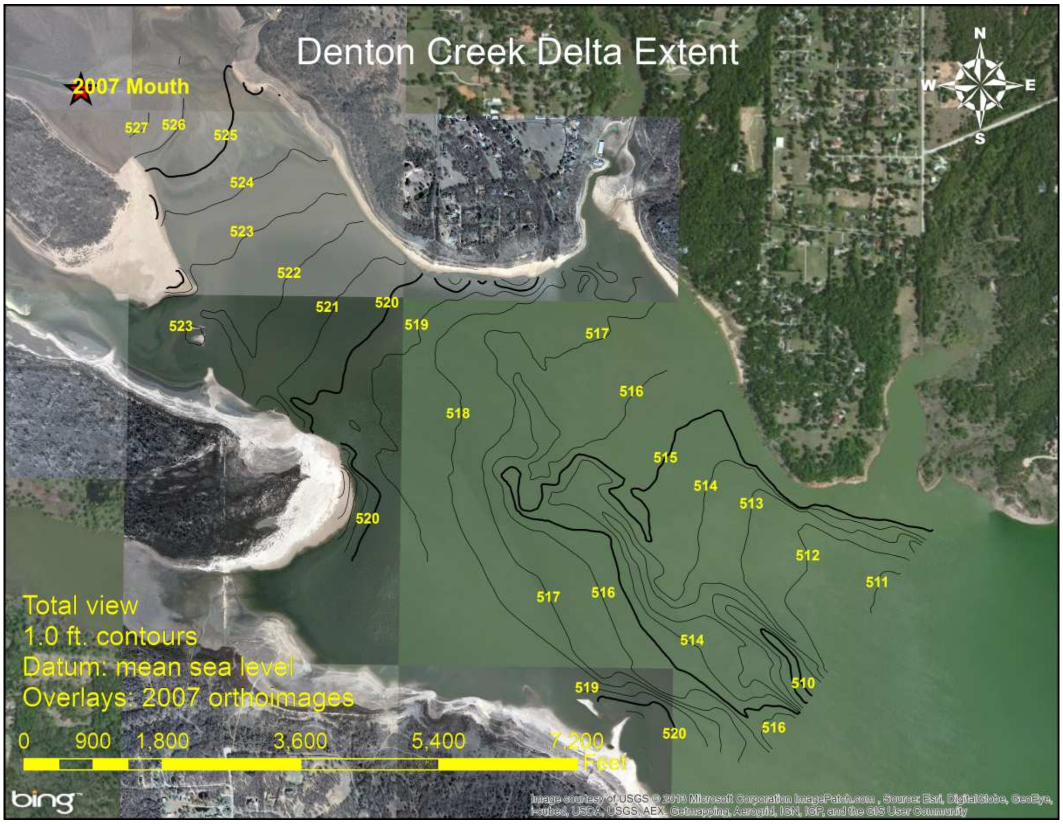


Figure 3-23 Bathymetry map of the Denton Creek prodelta extent. Contour intervals are 1.0 ft. The Denton Creek mouth is indicated by a star. Map generation: Esri® ArcMap™ 10.1. Background image: USGS © 2013 Microsoft Corporation ImagePatch.com. Overlays: USGS Earth Explorer, NCTCOG

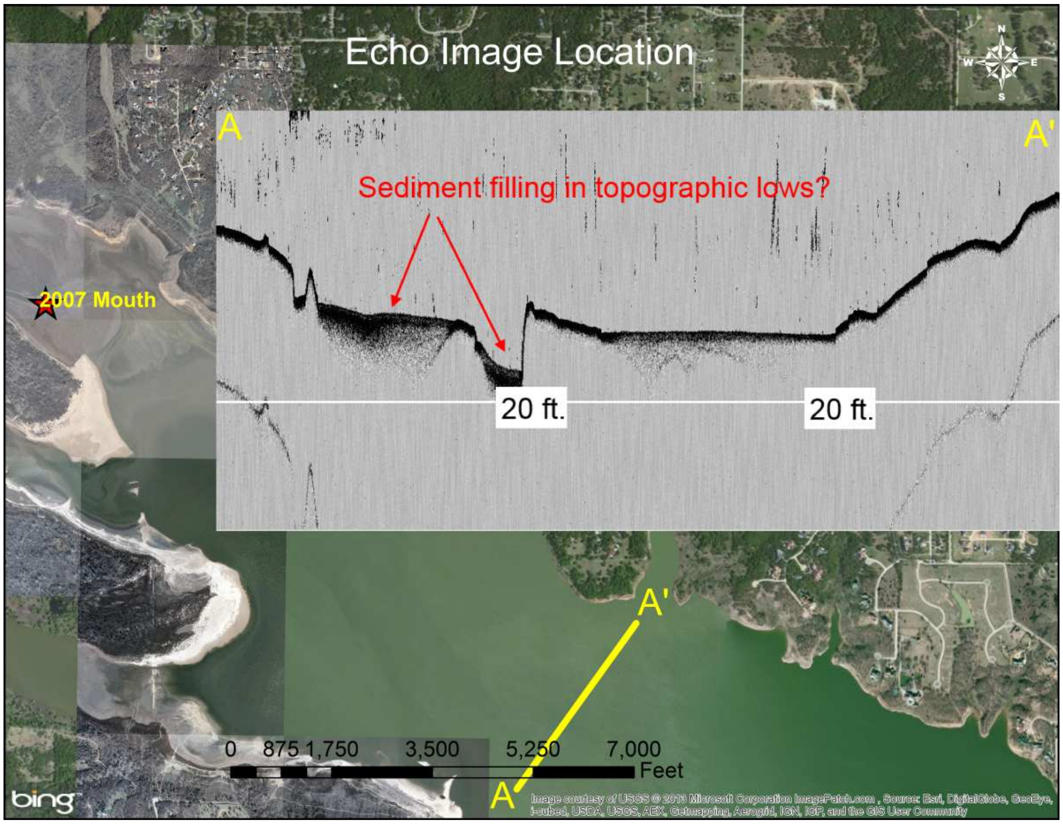


Figure 3-24 Map and echo location image showing sedimentation of topographic lows. Location of the cross-sectional echo image is from A to A' on the underlying map. Map generation: Esri® ArcMap™ 10.1. Background image: USGS © 2013 Microsoft Corporation ImagePatch.com. Overlays: USGS Earth Explorer, NCTCOG

3-3.2 Channel Mouth

The Denton Creek Channel mouth as defined in the 2007 orthoimages represents the location of the highest elevation water must pass in order to flow into Grapevine Reservoir (Figure 3-25). There is at least a four foot rise in elevation over the last 1,200 ft (366 m) of the channel. Extrapolation of channel and prodelta data points to the mouth location suggests that this increase in elevation may be as much as 6 ft

(1.8 m). In order for the channel to advance and maintain upstream channel depths, this material must be removed via erosion.

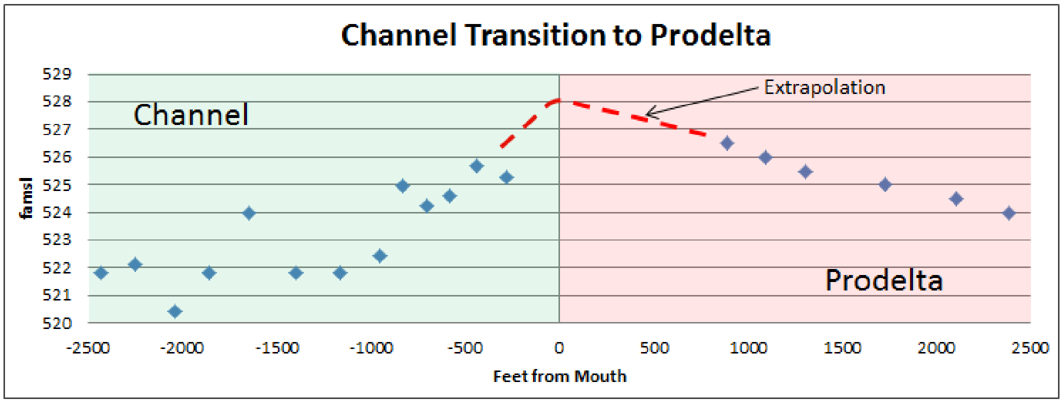


Figure 3-25 Channel transition to prodelta.
Channel thalweg elevations are on the left, prodelta elevations on the right. Extrapolation of elevations is indicated by red dashed line. Negative distances are upstream from the mouth, positive distances are basinward of the mouth.

Effects of prodelta erosion can be seen in the 2007 high resolution orthoimages (Figure 3-26). On the south side of the channel at the mouth and areas basinward of the mouth it appears that clays and sands have been blasted from the channel and plastered just south of the channel on the prodelta. From the mouth and basinward within the depression that coincides with the pre-impoundment channel, braided rivulets up to 6 ft (1.8 m) in width crisscross each other. As previously shown over areas upstream of the mouth, topographic irregularities are apparent within the channel with their long axis parallel to the flow direction (Figure 3-8). These irregularities were prolific during bottom sampling over the last 3,600 ft (1097 m) of channel.

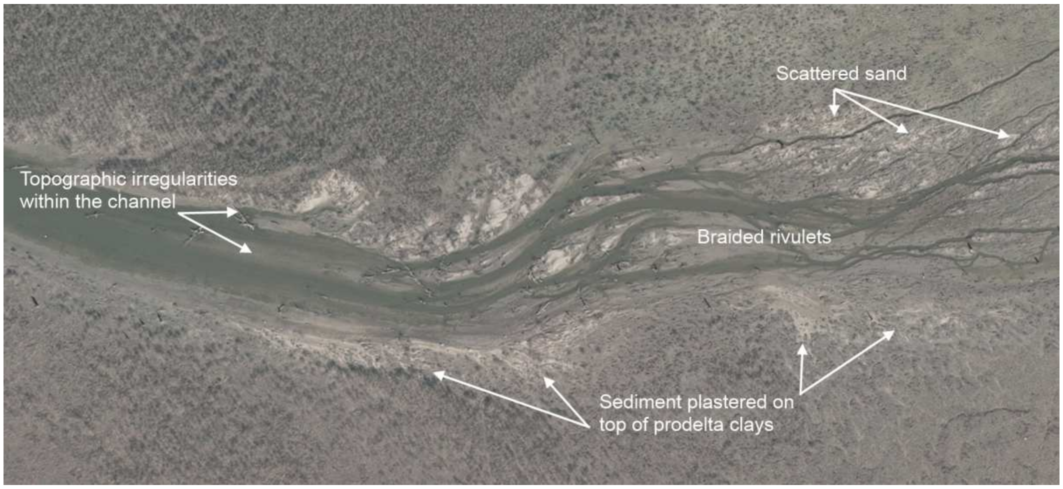


Figure 3-26 Denton Creek mouth erosion and deposition.
2007 high resolution orthoimage source: USGS Earth Explorer, NCTCOG

3-3.3 Prodelta Gouges

Gouge cores were sampled to a depth of 3.28 ft (1 m) across the prodelta basinward and perpendicular to the mouth (Figure 3-27). These gouge cores revealed consistency in sediment composition. In all, 18 gouge cores were taken across the prodelta; each core was sampled at intervals of 0.33 ft (0.1 m). All 180 samples are classified as clay. Only the sample for gouge 18 showed any silt component and it was approximately 30% silt at 3.28 ft (1 m). However, consistency of clay did vary in gouge samples, soft highly liquid clay overlaid hard clays. Gouge locations plotted on the 2007 high resolution orthoimage and cross referenced by depth to hard clays revealed that this depth corresponded to the depression in the prodelta (Figure 3-27). As previously presented, this depression overlies the pre-impoundment channel and is 0.1 to 0.2 ft (0.3 to 0.6 m) deep based on bathymetry mapping (Figure 3-14, D).

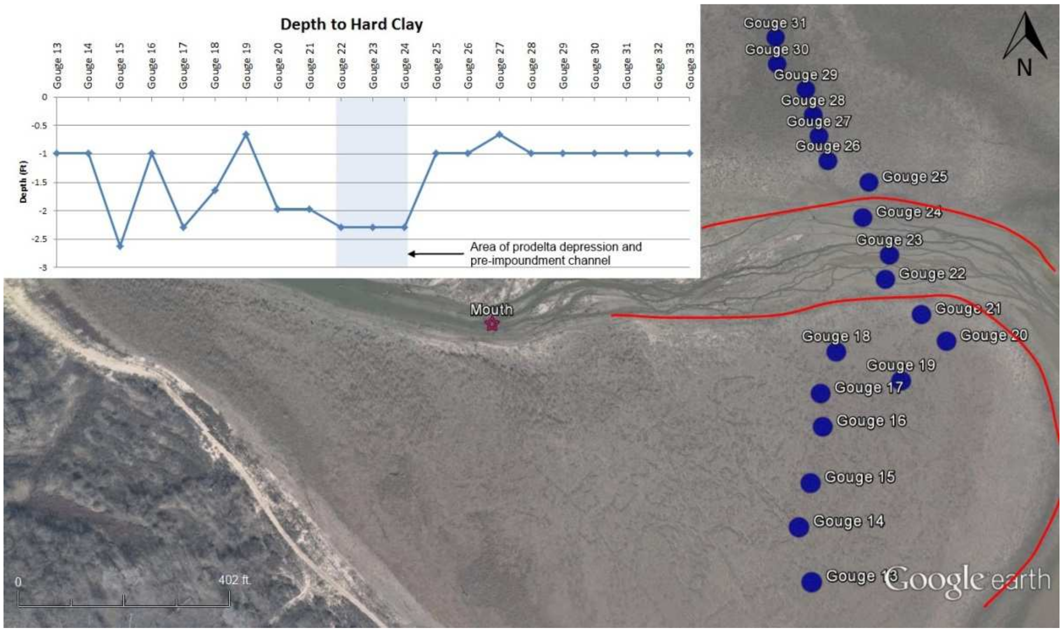


Figure 3-27 Prodelta gouge locations and graph showing depth to hard clay. Gouge locations indicated by blue circles on map. Prodelta depression indicated by red lines. Blue zone on graph corresponds to the area of the prodelta depression. Graph shows depth to hard clays from delta top. Map of gouge locations generated in Google Earth Pro. Ortho image source: USGS Earth Explorer, NCTCOG.

Chapter 4 Discussion

4-1 Denton Creek

Within the study area, the Denton Creek consists of a single channel that delivers delta building sediment to Grapevine Reservoir. This section addresses the morphology of Denton Creek and aspects of bedload, sand accumulations, and the channel mouth as they pertain to the two study hypotheses: (1) The distributary channel is non-bifurcating because sand load is not reaching the mouth of the river; and (2) Mouth bar sands do accumulate, but not to the point of bifurcation due to infrequent large flow events removing the mouth bars.

4-1.1 Morphology

Reservoir levels, sediment supply, and channel flow velocities have acted together to modify areas of Denton Creek. Upstream of the study area, Denton Creek is considered a meandering river with wide bends and point bars (Schumm, 1985).

This study found that the character of Denton Creek changed within the study area, as the channel widened considerably and backwater from Grapevine Reservoir drowned pre-existing point bars. After impoundment and fill-up, levees that flanked Denton Creek became submerged in areas downstream (north) of the Flower Mound boat ramp. Although aerial photographs between 1957 and 1968 were not available for analysis, other evidence indicates it is likely that Denton Creek levees remained subaerial in areas west of the Flower Mound boat ramp after reservoir fill-up. In this area, levee slopes are steeper than levee slopes in areas further downstream, and levee heights are comparable with levee heights more than 2 mi (3.2 km) upstream. Also in this area, the levees are often topped with mature trees. Additionally, 2012 channel dimensions west of the boat ramp were quite different than those at locations downstream; widths were smaller, and depths and cross sectional areas were greater. However, the channel north and east of the boat ramp has been modified from the original river form.

From the boat ramp northward along the straightaway, the channel widened greatly and cross sectional area decreased. Here the modern channel was filled with standing pre-impoundment timber that once grew on the levees or adjacent floodplain of the pre-impoundment creek (Figure 3-11). Cross sectional areas stabilized near the beginning of the straightaway and maintained a fairly constant level for about 2,800 ft (853 m) past the straightaway, suggesting that an equilibrium point is being reached over this section. Sand deposits in the straightaway indicate aggradation has occurred; whereas, very few sand deposits were observed in the 2,800 ft of channel past the straightaway. The bottom here was mostly harder clays and irregular at times, suggesting that this area may have recently undergone incision of prodelta clays.

Within the study area, the cross sectional area, depth, and width varied considerably over the last mile of channel. From about 4,900 to 3,600 ft (1,493 to 1,097 m) the thalweg shallowed to a minimum depth at an elevation of 526.58 famsl (160.50 mamsl). Downstream of this, about 2,000 ft (609.6 m) from the mouth, depths increased to a maximum at an elevation of 520.44 famsl (158.63 mamsl). From this point to the mouth, depths decreased again until the channel “tapered out”: at the mouth. This pattern is a common theme in tie channels, as their thalweg often rises to a point upstream of the mouth, deepens mouth-ward, and then rises again to the mouth. Rowland calls the initial thalweg shallowing feature a “sill”, but does not comment on the formation mechanism (Rowland, 2007). Lastly, this study found that over the last 1,000 ft (304.8 m) of the Denton Creek Channel, thalweg depth, width, and channel cross sectional area all decreased.

4-1.2 Bedload

It was hypothesized that bedload not reaching the mouth was a potential reason for the non-bifurcation of Denton Creek. Indeed, field work found that the majority of bedload existed more than a mile upstream from the mouth of the Denton Creek, and relatively few sands did reach the mouth. Sandy channel-bottom deposits were continuous over most of the upstream portion of the Denton Creek study area except for a small area near the Flower Mound boat ramp. This area spanned from 16,000 to 7,300 ft (4,877 to 2,225 m) from the western edge of the study area to the top of the long straightaway. The location of the small hiatus of sandy sediment was the tight meander bend near the boat ramp. These observations were consistent with findings on the Mississippi River where the absence of sands in tight bends indicates that bed material was likely transported via suspension over these areas and associated with more intensive bed shear stress and scour (Nittrourer, et al., 2011).

Over the last 7,300 ft (2,225 m), channel sands were discontinuous and the channel bottom was largely clay. This observation was consistent with findings in the Raccourci Old River tie channel, where the channel bottom upstream of the mouth consists of cohesive muds. It was speculated that high velocities over the stretch of the channel kept all sediment in suspension (Rowland & Dietrich, 2005). Both the reduction of Denton Creek Channel dimensions over this area and the finding of some near mouth sand accumulations (albeit small) would support this idea. A second and related possibility may rely on the nature of turbulent jet deposition (discussed in 4-2.2).

The bedload mapping of Denton Creek represents a snap shot in time with respect bedload location; but the possibility exists that the body of sand within the straightaway will advance forward as the channel continues to prograde. Forward moving sediment load has been tested experimentally and mathematically modeled. Results show that elongated deltas can form when the sediment source is not fixed, but instead is allowed to advance basinward. It was hypothesized that levees would be stable so long as they were “non-leaky” (Kim, et al., 2009). While of interest, these experiments were done with a sand feeding system creating sand levees and depositing sand basinward, and do not represent the conditions of Denton Creek, which has a lower sand load typical of natural channels.

4-1.3 Subaqueous Sand Dunes

One particular area west of the Flower Mound boat ramp (cross section 20) had obviously high sand accumulations (Figure 3-4). Cross sectional area (Figure 3-3) and thalweg depths (Figure 3-2) both decreased significantly over this area. These accumulations appeared to be stalled migrating dunes deposited in past large flow event(s). Sands were also evident in this location in the 2007 high resolution orthoimages. Based on their approximate size and profile, they would be classified as diminished small dunes (Carling, et al., 2000). Nonetheless, these sands greatly diminished the channel cross sectional area over that stretch of river (Figure 3-3). Other areas of sand accumulations were also associated with a reduction in cross sectional area, but to a lesser extent. The dunes visible in the photo of cross section 20 would represent an obstacle to flow during the next large event, and a source for future downstream deposits.

Large sand accumulations in Denton Creek may be due to backwater effect from Grapevine Reservoir. The area of backwater effect relies on several factors. The upstream distance a river can be affected by backwater is dependent on the slope of the river, as lower slopes result in an extended area influence by backwater. Additionally, if the receiving basin is small and basin water elevations fluctuate, the backwater zone also fluctuates.

Recent Mississippi River modeling indicates that drawdown of backwater due to turbulent spreading at the mouth can create both scour and deposition in areas upstream, depending on flow rates (Lamb, et al., 2012). Mississippi River modeling results indicate that during high velocity events, the effect of the spreading jet at the mouth causes upstream drawdown. This increases flow velocity in areas of the mouth and upstream, resulting in erosion over these areas. Upstream of the erosional area, the river alternates between areas of deposition and erosion. The authors also found that more frequent lower discharge events resulted in forced deposition (Lamb, et al., 2012). Backwater forced deposition is due to a decrease in velocity where the free flowing river encounters basin water. Mississippi River modeling results are difficult to extend to Denton Creek due to scaling issues and unknown parameters; however, the concept of backwater induced deposition and erosion should be applicable. It is likely that sand accumulations that represent choke points within Denton Creek are a result of backwater effect. The variability of sand accumulation locations at Denton Creek can be attributed to the backwater extent being affected by variable reservoir levels at the time of large flow events. The large sand accumulation at cross section 20 likely represents either a continued deposition at common extent of the backwater area, or an area of heavy deposition from a single flow event.

4-1.4 Mouth

The second hypothesis for the non-bifurcation of Denton Creek was that sands do accumulate; but these sands are subsequently removed during high flow events, and therefore not allowed to accumulate sufficiently to force bifurcation.

The critical process that leads to distributary bifurcation begins at the mouth of rivers. Mouth bars should form wherever a river meets a basin filled with water. A turbulent jet of fluid entering a basin filled with similar fluid, deposits subaerial levees. Basinward of the subaerial levees a mouth bar forms; this mouth bar leads to widening of the levees by disrupting flow, which in turn leads to bifurcation of the distributary channel. (Bates, 1953) (Axelsson, 1967) (Wright, 1977) (Edmonds & Slingerland, 2007). However, Denton Creek has prograded into Grapevine Reservoir about a mile without bifurcating. Additionally, other non-bifurcating single deltaic distributary channels exist in other man-made reservoirs as well as in natural settings in the form of tie channels (Rowland & Dietrich, 2005) (Rowland, et al., 2009).

Low water conditions prevented sampling at the mouth directly, but the absence of sands within the channel was observed from the 2007 high resolution orthoimages (Figure 3-26) and from nearby drill holes. These images reveal a great deal regarding processes in the area of the mouth.

The 2007 images reveal very few scattered sands at the mouth, compared with upstream deposits. This is consistent with the study observations. Some sand deposits were encountered around the mouth, but most were not within the bounds of the clay banks, but instead rested on the highest topographical locations adjacent to the channel banks and along channel levees. The 2007 images also reveal what appears to be very thin scattered sand on top of the prodelta basinward of the mouth. This area was covered by less than 2 ft (0.61 m) of water and could not be accessed or sampled. Gouge sampling was performed just basinward of the location of these scattered sands and results from gouge sampling revealed no sandy deposits reached this area, only clay (Figure 3-27).

Field observations at the mouth in combination with the aerial photographs showed that little or no sandy mouth bar existed. If a mouth bar exists, it is likely minor and located where the braided rivulets begin in the 2007 images (Figure 3-26). Based on shades of gray and apparent texture of sediment in the images, it appears that semi-cohesive material such as loamy sands, loams, and even highly-liquid soft clays have been blasted from the channel and plastered alongside of the channel. This is a reasonable assessment based on the grooved nature of the channel in this area and the fact that the channel continues to advance. For the channel to advance, prodelta clays must be removed, and with this in mind, a sandy mouth bar would not present an obstacle. If irremovable sands did accumulate at the mouth it would have already resulted in bifurcations. Upstream of the mouth, the channel thalweg was clay. Cross sections upstream of the mouth revealed sandy deposits at the channel margins that were fewer, smaller, and thinner compared with other deposits within the system. These findings support the hypothesis that mouth bar sands do accumulate, but not beyond the thickness of a veneer or to the point of bifurcation due to infrequent large flow events removing the mouth bars.

4-2 Mechanisms of Denton Creek Delta Progradation

Turbulent jet erosion and deposition is the driving force that accounts for the progradation of the Denton Creek Delta. In this section, a single mechanism (the turbulent jet) and the two main processes that account for the non-bifurcating progradation of the Denton Creek Delta are presented. These two processes together in essence create the channel and include: (1) advancing prodelta erosion in the area of the channel mouth and for some distance upstream; and (2) levee building through turbulent jet margin sedimentation. These two processes form a two component channel, a channel with a clay base providing lateral stability, and sandy levees that confine the turbulent jet upstream of the basin waters.

Also presented is a conceptual model describing how the turbulent jet and levee dimensions combined with basin size to create a self-sustaining process for continued progradation. This is followed by sections on channel widening and stability, both of which are related to (1) above.

Note that levee thickness is also enhanced by splaying and overbank deposition; this was beyond the scope of the study and is not addressed.

4-2.1 Prodelta Erosion and Channel Advancement

The first and lower component of the Delta Creek Channel was created by turbulent jet erosion of the prodelta clays basinward of the channel mouth.

The elevation of the Denton Creek Channel bottom rose between 4 and 6 ft (1.2 and 1.8 m) over the last 1,200 ft (366 m) of channel (Figure 3-25). Over this area the channel bottom was comprised primarily of prodelta clays. In front of the mouth were additional prodelta clays blocking further advancement. For the distributary to continue prograding, this body of sediment must be cut into and removed. Evidence shows that Denton Creek has continually advanced basinward following the channel path that pre-existed the prodelta deposits (Figure 3-14). The necessity of prograding river deltas to cut through cohesive mouth bar sediment in order to advance has been commented on (Ikeda, 1989). Ikeda postulates that once a cohesive mouth bar is cut, portions of the cohesive structure flank the channel and become the channel banks. This restricting feature prevents future lateral channel migration (Ikeda, 1989). In fact, cohesive oxbow fills are believed to act as limits that control Mississippi River meandering in places (Fisk, 1947). The fact that tie channels also cut into prodelta sediment in order to advance and have little or no migration has been noted (Rowland, 2007), but the method by which this is accomplished has not been addressed.

There are likely common factors that allow tie channels and other non-bifurcating channels to continually cut into cohesive prodelta sediment. Differences in prodelta sediment cohesiveness, differences in cohesiveness of the levees containing prodelta clays, and the action of the turbulent jet all likely have a role in where and how prodelta erosion occurs. These factors guide the progradational course of the Denton Creek Delta.

By adding polymers to sediment, physical modeling has shown that increased cohesion could lead to long lived distributary channels like the Mississippi River Bird-Foot Delta (Hoyal & Sheets, 2009). Through numerical modeling software, others have shown that cohesive end members lead to fewer bifurcations. Low cohesive sediment models predict fewer bifurcations, because the lower cohesive mouth bar is easily eroded by the turbulent jet; however, this end-member also leads to fan type deltas due to the lack of cohesive strength in the levees (Edmonds & Slingerland, 2010). In contrast, high cohesive sediment models predict well established levees that focus the erosive power of the jet toward cohesive mouth bar deposits. Also, the focused jet has the ability to redistribute cohesive mouth bar sediment basinward. This model predicts that highly cohesive sediment leads to prograding bird-foot like deltas (Edmonds & Slingerland, 2010). This author also comments that the presence and type of vegetation can also affect the cohesiveness of the sediment.

Differential cohesion laterally in front of the delta channel appears to be of importance, as soft highly-liquid clays are up to a magnitude less cohesive than hardened dewatered clays (Waltham, 2009). In this study, bottom sampling revealed soft clays occupying local topographic lows in areas near the mouth of the Denton Creek Channel. These clays had a consistency similar to pudding or half-melted ice cream. Bathymetry maps also indicate a preferential filling in of preexisting topographic lows (Figure 3-23) (Figure 3-24). The Denton Creek prodelta has built out over and filled in the preexisting flood plain, levees, and channel. Prodelta clays overlying the preexisting channel are thicker than prodelta clays in areas overlying the adjacent preexisting flood plain or levees. When prodelta clays are deposited they are soft and highly liquid; over time they become hardened through compaction and dewatering. The depression evident in the 2007 prodelta image directly overlies the preexisting channel (Figure 3-14, D). This depression is most likely the result of the compaction and dewatering of a thicker section of prodelta clays than that which rests on the adjacent levees or flood plain. Prodelta deposition, dewatering, and compaction are continuous processes. Thus, the prodelta deposits that override the preexisting channel should always represent the local topographic low and thus the preferred path of delta propagation. Also, a greater thickness of soft highly liquid clays should always occupy this local topographic low. Results from gouge data basinward of the channel on the prodelta supported this, as they showed a greater depth to hard clays over the preexisting channel than those areas adjacent to the channel (Figure 3-27). Data collected through bottom sampling also supported this, in that topographical lows within the channel contained the softest, most highly liquid clays. An example of this can be seen in Figure 3-8.

At some depth adjacent to the soft erodible clays deposited within the channel are pre-impoundment levees. The pre-impoundment levees should have higher cohesion than the clays deposited between them, because they were unsaturated and rooted by trees prior to impoundment. When a large flow event occurs, the turbulent jet is focused at the deposits directly in front of the jet. The decreasing channel parameters over the last 1,000 ft (305 m) would act like a nozzle on a garden hose, further intensifying this focus. Because the current channel has followed the preexisting channel since impoundment, there has always been a low area of relatively thicker soft clays directly in front of the jet to erode. The force of the turbulent jet would naturally erode the path of least resistance.

If the cohesive rooted pre-impoundment levees are not too deep they would limit lateral expansion of the channel at depth.

Occasional exposure of the prodelta would promote drying and cracking of the clays; and based on photographic evidence, desiccation and fragmentation likely aids in their erosion (Figure 3-8). Evidence that this process has occurred was the inclusion of hardened clay blocks and cobbles contained within the otherwise soft highly liquid clays collected in both bottom sampling and gouge cores. Another factor that may aid in erosion at the mouth would be large trees that are forced across the prodelta rise during flood events. These would serve as battering rams to the delta-mouth mound during high flows. The process of prodelta erosion has allowed the channel to advance forward even following tight bends like the one in the far northern end of the study area since impoundment.

Besides the numerical modeling of cohesion in river dominated deltas discussed above (Edmonds & Slingerland, 2010); to date, the erosional aspects of a turbulent jet are nearly absent in the literature, as most of the focus has been on turbulent jet deposition. Although not fully comparable due to the use of non-cohesive sediments, Hoyal physically modeled the erosional aspect of a turbulent jet (Hoyal, et al., 2003). He called the area of erosion an “incipient channel.” His modeling results show a zone of erosion with a length 4 to 8 times the orifice diameter. The end of the erosional area tapers upward to the depositional surface (Hoyal, et al., 2003). Hoyal postulates that the larger flute structures found in nature are actually from this type of erosion, and once they are filled with sediment these would look like channel fills. The tapering geometry of erosional features that Hoyal modeled is very similar to the structure of the Denton Creek Channel approaching the mouth. Unfortunately, the channel width to scour length ratio is difficult to determine in a natural system. The levees taper basinward, so the distance from the end of the orifice to the end of the channel erosion taper would be dependent on water levels. However, map tool measured distances based on the 2007 orthoimages and best estimates would put the Denton Creek scour in the neighborhood of 8-10 orifice lengths basinward.

Another reservoir delta and distributary channel that has been investigated is the Red River Delta in Lake Texoma (Olariu & Bhattacharya, 2012). Like the Denton Creek Delta, it has followed the preexisting topography but not so precisely. Aerial photographs show that initially the Red River Delta followed the old channel path, but sometime between 1955 and 1966 it avulsed from this path cutting off a wide meander but again rejoined the original channel down dip and continued to prograde over it. From this point forward the delta channel appears to have followed the preexisting channel for perhaps as much as 4 miles basinward, before losing adherence to the preexisting channel. From this point forward the Red River Delta has prograded straighter than the preexisting topography along the north shore. The path of the Red River Delta is attributed to hyperpycnal flows following the steepest gradient basinward, and areas of elongation are attributed to high discharges (Olariu & Bhattacharya, 2012).

Differences in adherence to the preexisting channel of the Denton Creek Channel and the Red River Channel may be attributed to differences in processes, sediment load, etc.; however, similarities suggest a shared underlying mechanism. The modern Denton Creek Channel owes its adherence to the old channel due the soft clays that overlie the preexisting channel.

I speculate that as the Denton Creek Channel continues to advance, the adherence to the preexisting channel may wane, and the modern channel is likely to become straighter than the preexisting channel. As addressed, soft prodelta clays overriding the preexisting channel have played an important role in the erosional path of the advancing delta. As the Denton Creek Channel continues to advance basinward, the prodelta clay thickness will become greater over all terrain. The relative thickness of clays overlying the channel will decrease, and so will the effect of dewatering and compaction that has resulted in the depression overlying the preexisting channel. Furthermore, there should be a point of balance where shear stress emitted by the turbulent jet is greater than the cohesive strength of all sediment basinward. In this case the channel would become straighter and the course of prograding channel would no longer precisely follow the pre-impoundment channel. Evidence for this can be seen in the 2007 images and photographs (Figure 3-6) (Figure 3-7). These images show an area of channel shallowing and widening where a bend was encountered over the preexisting channel. It is likely that the influence of clay dewatering has become less at this location and the shear stress emitted by the turbulent jet has straightened the bend by eroding additional prodelta clays that were adjacent to the preexisting channel.

Another factor that may contribute to channel deepening in the area of the mouth and upstream of the mouth was hypothesized by E. W. Lane in 1957. Lane realized that many rivers were deeper near their mouths than at points upstream. As previously mentioned, the Denton Creek thalweg rises to a topographic high about 3,600 ft (1,097 m) from the mouth, deepens toward the mouth, then shallows to the mouth the last 1,000 ft (305 m). Lane reasoned that during high flow events where a river enters a basin, jet plume spreading would fix the water elevation at the mouth and drawdown of the elevated body of water upstream would cause flow acceleration. Recently this hypothesis was model tested by coupling jet spreading with backwater effect during high flow events. The model shows that a spreading plume draws down the backwater area during high flow. This leads to flow acceleration at the mouth and areas upstream, which further leads to channel scour at the mouth and for some distance upstream (Lamb, et al., 2012). This effect would essentially increase the velocity of the bounded jet at the mouth and for some distance upstream, and may add to the influence of jet scour in the mouth area of Denton Creek. Several factors prohibit relating the dimensions and magnitudes of erosion and deposition modeled to Denton Creek. Discharge rates at the mouth of Denton Creek are unknown, and flow rates recorded upstream by the flow gage near Justin Texas are more than an order of magnitude less than those modeled. The Mississippi River has very low slopes and the slope of Denton Creek is unknown. The Mississippi River has a fixed elevation at the mouth during a flow event; whereas, the elevation of Grapevine Reservoir can increase rapidly. Modeling focused on very large discharge events. These events generated upstream erosion hundreds of kilometers from the mouth. In order to display the larger events, the resolution of what occurred in the smallest flow event modeled was lost in the scale required to show the effect of the larger events. However, the principle of drawdown due to jet spreading at the mouth during large events likely influences the velocity of turbulent jet upstream of the mouth at Denton Creek. Lastly, there is a possibility that a feedback mechanism could exist between levee slopes and the increase in elevation of water backed up at the mouth.

4-2.2 Levee Building through Turbulent Jet Sedimentation

Levees compose the second and upper component of the Denton Creek Channel. The primary mechanism for the formation of levees which compose the Denton Creek Delta is by turbulent jet margin sedimentation. This sedimentation begins at the mouth or orifice and extends some distance basinward from the mouth. As previously discussed, the location of the mouth is relative to reservoir elevation, and as the elevation rises the mouth and area of sedimentation would migrate upstream.

The Denton Creek Delta has prograded over a mile in total since impoundment. It has prograded from the northern end of the straightaway to its current position (Figure 3-14, A). The components of the delta are the substantial northern bounding levee and the southern levee which is essentially smeared along the southern shore in-filling pre-impoundment shoreline irregularities of Grapevine Reservoir (Figure 3-16).

Sedimentation at the margins of a jet has long been recognized as a levee growth mechanism (Bates, 1953) (Axelsson, 1967) (Wright, 1977) (Edmonds & Slingerland, 2010). Recent investigations into non-bifurcating tie channels have furthered the knowledge of this process (Rowland & Dietrich, 2005) (Rowland, 2007) (Rowland, et al., 2009), and has spurred others to advance it even further (Falcini & Jerolmack, 2010). Jet sedimentation is based on principles of fluid dynamics and physics. Simply stated, when a fluid with velocity is emitted from an orifice into a quiescent basin filled with similar fluid, the jet spreads due to turbulent mixing with the basin fluid at the margins. This results in a Gaussian style reduction in velocity, which in turn induces sedimentation along the lower velocity margins, resulting in the growth of subaqueous levees (Figure 1-2). Opinions and experimental results on orifice width relative distances of levee growth vary, but most agree it is somewhere between 4 and 8 orifice widths.

Through flume experiments, Rowland was able to produce leveed channels similar to tie channels. He was also able to determine critical factors that lead to sedimentation at the margins as opposed to the centerline. One of these factors is the high lateral diffusion of sediment. This factor likely relies on a two dimensional turbulent structure that meanders within the jet (Rowland, 2007) (Rowland, et al., 2009). An example of this structure can be seen in the Ouachita River tie channel example (Figure 1-5, A). Rowland also found that sediment settling velocities influence the morphology of the levees (Figure 4-1); higher settling velocities result in straighter levees and lower settling velocities result in levees that flared more toward the toe (Rowland, 2007).

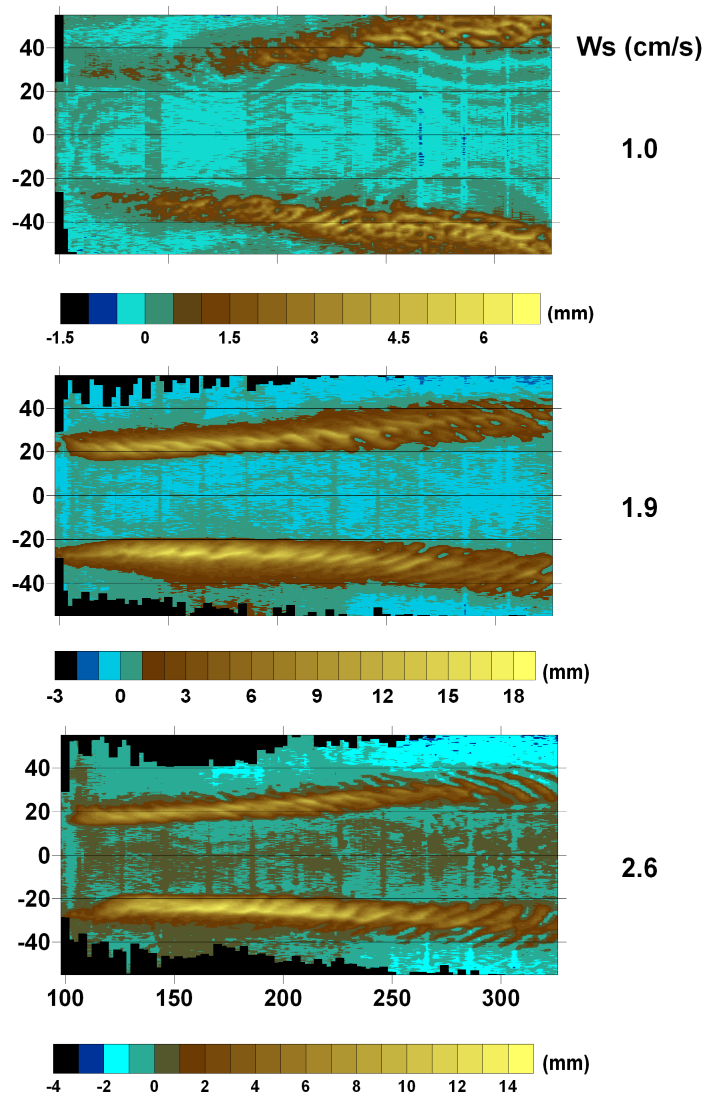


Figure 4-1 Rowland's flume modeled levee morphology based on settling velocities. Vertical axis is distance from centerline (cm); horizontal axis is distance from the orifice (cm). Color bar shows levee height (mm). Bold numbers located to the right of images are particle settling velocities (cm/s). (From Rowland 2007)

The structure of Denton Creek's northern levee as viewed in satellite images was consistent with similar images of tie channel levee morphology. Field observations of the northern levee at Denton Creek were consistent with descriptions of tie channel levee morphology (Rowland & Dietrich, 2005) (Rowland, 2007).

Results from flume experiments show that jet margin sedimentation results in longitudinal sediment deposits flanking the channel. These deposits taper away from the channel axis at an acute angle in the downstream direction. In a cross sectional profile the highest sediment accumulation is near the channel, thins perpendicular to the channel axis, and is reminiscent of the cross sectional profile of a wing (Figure 4-2). The cross sectional profile of Denton Creek's northern levee (Figure 3-17) is representative of experimental jet margin sedimentation results of Rowland and others and has a wing-like profile. Satellite images, vegetation growth, and field observations indicate that the northern levee has this wing-like taper from the far northern end of the reservoir to the tip of the levee.

Lastly, photographic evidence acquired during field work shows a sand deposit that is most likely from a single turbulent jet margin sedimentation event (Figure 3-18). The photo shows a long V-shaped sand deposit with the apex of the V in the upstream direction. The sand appears to have emanated from the channel when the reservoir level was higher and the mouth position was further upstream than in the photo. The channel also has an appearance similar to the 1.0 settling velocity model in Figure 4-1.

Figure 4-2 Rowland's flume experiment with 1.9 cm/s settling velocity particles. Oblique view with 20 cm grid shows experimental levee sedimentation.

Figure 3-18 shows an early stage of levee growth. Levee growth begins with exposure of emergent prodelta clays or proto-levee crests from sediment blasted from the channel mouth. High points along the channel margin catch woody debris. This woody debris is often preserved at the base of the levee or in the lower portions of the levee (Figure 3-19). Jet margin sands are deposited on top of prodelta clays that flank the channel base. Initial sand deposits spend the majority of time subaqueously and are reworked with finer sediment by waves or are preserved as sands by clay drapes. Along the sandy margin nearest the lake in Figure 3-18 the sands grade to loams at the base of the deposit. Reworking results in loamy deposits on top of the prodelta clays or mixed in with woody debris (Figure 3-19). Through successive sedimentation events levee height increases and levees spend more time subaerially. This minimizes the exposure to finer sediment. Observations and photographic evidence indicate that the clay component in levees decreases and the sand component increases with increased levee height.

4-2.3 Conceptual Model for Self-Sustaining Levee Progradation

Continual progradation and basinward decreasing levee height is a shared feature for both tie channels (Rowland, 2007) and for non-bifurcating channels in reservoirs. I propose that this is a result of a self-sustained process.

Small basins or reservoirs like Grapevine Reservoir can rise rapidly in a major flood event. Grapevine Reservoir is capable of rising 7 ft (2.1 m) or more in a 24 hour period. Because the height of the Denton Creek levees decreases basinward; in a sustained flow event, with rising basin water, the orifice of the turbulent jet and the zone of the jet margin deposition would gradually move upstream contemporaneously. This would result in a long linear zone of sedimentation that flanks each side of the channel. Each episode of this process (combined with channel erosion) would extend the levees down dip and increase the height of the levees up dip. This model creates a self-sustaining process by which levee height is increased, levee taper is maintained, and levee progradation can be sustained by adding of material onto the levee well after the mouth has prograded past a given point.

4-2.4 Channel Widening

An additional aspect of channel erosion is widening of the channel. Image analysis indicates that the modern channel overlies the channel that preexisted impoundment (Figure 3-14). Field evidence suggests widening of the channel occurred at all points downstream of the Flower Mound boat ramp. West of the boat ramp, levee to levee channel widths averaged about 100 ft (30 m) based on field measurements from 2012 (Figure 3-9, green triangles). Downstream over the straightaway most channel widths ranged from 150 to 200 ft (46 to 61 m) and the modern channel contained remnant vertical tree stumps that obviously preexisted impoundment and resided on the levees or adjacent floodplain (Figure 3-11). Areas downstream of the straightaway varied in width, but over the last 5,000 ft (1524 m) channel widths were commonly between 120 and 170 ft (37 to 52 m). Similar to the straightaway, the channel in this area also contained remnant vertical tree stumps that marked the preexisting channel margins (Figure 3-12). The tree stumps were much nearer to the bank in the photograph taken at about 4,000 ft than in the straightaway. Evidence of recent layered erosion also existed in places over this interval (Figure 3-7).

Based on this evidence, widening of the channel has occurred by erosion of levee sediments and/or prodelta clays that were proximal to the preexisting channel and were deposited on top of pre-impoundment levees or the very near floodplain. Widening is likely a channel carrying capacity response in areas where prodelta clays were not removed to a sufficient depth. More widening has occurred over the area of the straightaway, but the straightaway appears to be stable now. Evidence indicates that the channel further downstream does not have sufficient carrying capacity and is still in the erosional phase.

4-2.5 Channel Stability

The Denton Creek Channel is highly stable. It has not meandered and continues to prograde basinward. Based on historical satellite images and aerial photographs, other similar channels that are prograding into reservoirs show similar stability over time. Tie channels also have the same characteristic stability, and it is likely based on the same or similar mechanism(s). The most likely explanation for this is that cohesive clays compose the bottom portion of the channel and control the focus direction of the turbulent jet. This minimizes lateral erosion and maximizes forward erosion. The levees are the weak link in this model; but as shown, they contain clay drapes and once they reach a certain height they become covered with trees and their cohesiveness increases.

4-3 Connectivity

The aspects of potential connectivity within the deltaic system of Denton Creek pertain to its similarities with tie channel deltas which occur in natural systems and should be in the rock record. As previously discussed, the levees of Denton Creek are morphologically similar to tie channel levees. Sand component reported in tie channel levees from multiple geographic locations ranged from 11% to 68% (Rowland, 2007).

Continuous bedload in Denton Creek was more than a mile upstream of the mouth, but Denton Creek has the potential to carry anything that is eroded upstream. In contrast, tie channels connect a flood plain to a river and “tap” the river some distance above the riverbed. Therefore, tie channels may not receive the coarsest sediment except during high flow events (Hull, 2012). Bedload composition reported in tie channels from different geographical locations appears to be even more varied from 2% to 95% (Rowland, 2007). However, the data reported for each channel bed consisted of only one sample and may not be representative of bedload sand quantities. Whether or not sand is a bedload component in tie channels is also related to the quantity of sand that the main channel carries, and like Denton Creek, tie channels can have sand deposits that lag behind levees (Hull & Holbrook, 2012).

Denton Creek had two continuous sand bodies, the channel bed sands and the levee sands. The channel sands were continuous in areas upstream of the mouth and became thicker and contained less clay in the up dip direction. Similarly, the levees contained layered sands and loams at the base, the sand component increased in the upward direction, and the thickness of the levees increased up dip direction. The levee sands extended much further into the basin than did the channel sands. The widths of the levees were upwards of 600 ft (183 m) in places and they are topped with several feet of clean sands.

In a natural system, levees such as these would represent a continuous body of sand and sandy sediment connecting back up dip to the source river. Both levee and channel sands in non-bifurcating floodplain deltas may provide a link to channel sands. Of these, levee sands may represent a more substantial link with regards to potential connectivity.

Chapter 5 Conclusion

The Denton Creek Delta has been prograding into Grapevine Reservoir since impoundment in1952. Like the deltas in many other man-made reservoirs, it has a single non-bifurcating channel. The morphological similarities between these deltaic-channels and tie channel deltas in natural settings are numerous and they should be considered analogues. Deltas like the one at Denton Creek are excellent laboratories for the study of processes that control the growth of natural deltas due to the abundance of available data.

Backwater effect from the reservoir lowers upstream flow velocities. This causes large sand deposits to occur, essentially plugging the creek in places. The majority of sand deposits are more than 8,000 ft (2438 m) upstream of the mouth. During high flow events some of these sands are mobilized, but the majority of sands are deposited on the levees and little or no mouth bar is formed.

The delta has prograded into Grapevine Reservoir adhering to the pre-impoundment channel for over a mile with little alteration. The hydrodynamic mechanism that controls this adherence is that of a turbulent jet. The actions of the turbulent jet create a dynamic two-phase self-propagating process, whereby eroding soft semi-cohesive prodelta clay while simultaneously building sandy levees. Prodelta clays exist in greater thickness, are softer, and have higher water content over the pre-impoundment channel than in adjacent areas. These clays represent the path of least resistance and lie directly in front of the advancing channel.

The clay bottom channel decreases in width and tapers upward to the prodelta rise. In large flow events, the reduction in channel dimensions approaching the mouth further intensifies and focuses the jet at the prodelta rise. Prodelta clays and any mouth bar sand deposits are sent basinward or are plastered onto the channel margins by the force of the jet, while sands are contemporaneously deposited at the jet margins. Erosion into prodelta clays and channel deepening continues for some distance upstream and results in a very uneven channel bottom. Erosion of prodelta clays basinward of the mouth, near mouth channel deepening, and jet margin sedimentation are the main factors that maintain adherence to the preexisting channel, prevent lateral migration, and promote progradation.

Evidence shows that the modern channel is wider than the preexisting channel. The soft clays that overlie the preexisting channel are flanked at some depth by pre-impoundment levees. Remnant vertical tree stumps within the modern channel mark the position of the preexisting levees or adjacent floodplain. Typically, the deeper part of the modern channel resides between these remnant tree stumps. Layered erosion lateral to the channel is seen over the last 5,000 ft (1,524 m) and is more prolific where the channel cross sectional area is low.

Basin size and levee taper play important roles in a feedback mechanism that aids in channel advancement and erosion. In a sustained flow event the orifice of the spreading turbulent jet gradually moves upstream due to rising basin level and basinward tapering levees. The area of jet margin sedimentation moves upstream while at the same time eroding the channel bottom. This results in lengthening of the area of jet margin levee sedimentation on the channel flanks. This gradual migration would continue upstream for the duration of the event depositing sands on the levees at all points along the way. Repetition of this process erodes the mouth, extends the levees basinward, deepens or widens the channel, and maintains the basinward taper of the levees that confine the jet; which together allows for repetition of the process, and continued progradation without bifurcation.

5-1 Future Work

There is still much to be learned about the mechanisms and processes described herein. Specific areas for further study include the self-promoting processes of prodelta erosion, the influence of the upward tapering channel at the mouth on focusing a turbulent jet, and the self-maintenance of basinward dipping levees. Questions would include: What physical parameters are required for a jet to erode prodelta clay? Can this process be physically modeled in a laboratory? Can the conceptual model of upstream migration of a turbulent jet in response to rising basin levels be physically or numerically modeled as a self-sustained system? Is a small basin necessary? What are the necessary sediment requirements for the non-bifurcating behavior?

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