ABSTRACT

Modeling Channel Erosion in Cohesive Streams of the Blackland Prairie,
Texas at the Watershed Scale

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Stream bank erosion is a product of submerged and subaerial processes. The goal of this research was to assess the application of the submerged jet test to predict erosion of cohesive stream banks in the Blackland Prairie of North Central Texas, an area with over 40% of the State's population. *In situ* erosion monitoring was conducted by utilizing erosion pins and water level loggers at seven field sites with contributing drainage areas of 5-239 square kilometers. Erosion pins were placed at two locations on the cutbank wall and monitored over one year.

Erosion rates during the monitoring period were a function of bank height and flow duration. Submerged jet test values from samples taken at the same locations as the erosion pins predicted erodibility of the material ranged from 0.0034-0.0065 cm^3/N-s. Erosion pins indicated 30.35-572.00 mm of loss. The predicted erosion coefficients from the jet test, tractive force, and cumulative flow duration was within 31% of the field erosion. This study evaluates the first *in situ* testing of the erodibility of cohesive stream banks with cumulative flow duration, cumulative tractive force, and subaerial processes.

Modeling Channel Erosion in Cohesive Streams of the Blackland Prairie,
Texas at the Watershed Scale

by

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A Thesis

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CHAPTER ONE

Introduction

Urbanization increases storm runoff peaks, frequencies, and volume, leading to channel downcutting and widening, and increase sediment loads (Staley et al., 2006). According to the U.S Environmental Protection Agency (USEPA, 2005), sediment is the fourth leading cause of water quality impairment nationwide and costs approximately $16 billion in damage annually in North America (ARS, 2003). Studies show that 575,000 stream bank miles are actively eroding and of that 142,000 stream bank miles have more severe erosion problems. In total these streams require an average annual cost of $1.1 billion for management (USACE, 1981). These stream banks are incised and eroding at accelerated rates due to urbanization (Simon and Rinaldi, 2000), which accounts for as much as 90 percent of watershed sediment yields and estimated bank retreat rates of 1.5 to 1100 mm/year (Grissenger et al., 1981a; Trimble, 1997; Lawler et al., 1999; Prosser et al., 2000; Simon et al., 2000). Grenier (1982) reports that in Texas about 40 percent of the gross sheet and rill erosion is attributed to gully and stream bank erosion. Estimates of a half a million dollars have been allocated to loss due to channel erosion in the Dallas, Texas area (Allen and Narramore, 1985). These costs have risen by a factor of 100 due to increased urbanization (Allen et al., 1997). Excess stream bank erosion reduces water quality through increased turbidity and the transport of sediment-bound pollutants, which can cause algal blooms and damage the ecosystem through eutrophication (Staley et al., 2006). In addition to water quality impairment, stream bank retreats affect floodplain residents, riparian ecosystems, bridges, and other stream-side structures (ASCE, 1998;

Wynn and Mostaghimi, 2006). Accurate stream bank erosion rates and channel retreat prediction is necessary for the development of better sediment total maximum daily load (TMDL) determinations and watershed management.

Changes in watershed land use, river regulation, or channel engineering may change stream flow and/or sediment regimes. These may cause instabilities in stream form (Wynn, 2004). A combination of three processes that cause stream bank erosion: subaerial processes and erosion, fluvial entrainment, and mass wasteing (Wolman, 1959; Lawler, 1992 and 1995).

Subaerial Processes

Subaerial processes (SAP) are climatic-related phenomena (e.g. frost heave, soil desiccation, wet and dry cycles), weaken the stream bank face by reducing soil strength prior to fluvial erosion (Thorne, 1982). SAP control stream bank retreat in the upper-most reaches of river systems by weakening the soil surface and depositing the eroded soil directly to the stream channel. SAP makes banks more susceptible to flow erosion by reducing the packing density of soils (Thorne and Tovey, 1981; Abernethy and Rutherfurd, 1998). SAP are thought of as “preparatory processes” as they increase soil erodibility rather than “erosive” processes (Wolman, 1959; Thorne, 1990; Lawler, 1993; Green et al., 1999; Couper and Maddock, 2001).

Stream bank desiccation is a subaerial process that creates soil peds and aggregates, which have little resistance to erosion, and can create conditions for soil slacking (Thorne, 1982; Robinson et al., 2000; Wynn, 2004). Slaking occurs when the pore air pressure in the soil increases prior to soil being suddenly immersed in water. This can cause vertical tension cracks which reduce the structural strength of the stream bank (Thorne, 1982). Tension cracks increase soil permeability and may lead to the development of higher pore water pressures, which reduce bank stability (Greenway, 1987; Davidson et al., 1991). Cycles of wetting and drying are known to influence bank erodibility more than composition (Knighton, 1973), and repeated cycles of this decreases aggregate size in clay soils (Shiel et al., 1988) making the soil more prone to entrainment during storm events. According to Shakoor and Rodgers (1992), the process of slaking is the main cause of erosive activity of shales and claystones. Stream banks with high silt-clay content are prone to erosion. Soil desiccation may be the dominate cause of bank retreat (Green et al., 1999; Prosser et al., 2000; Couper and Maddock, 2001).

Conversely, several researchers have shown that drier soils are more resistant to fluvial entrainment (Wolman, 1959; Knighton, 1973; Hooke, 1979). Studies by Thorne and Tovey (1981) suggest that soils with high silt-clay content increase their resistance to erosion by flowing water relative to cohesionless material (*e.g.* sandy soils). They have shown soil desiccation to actually increase soil strength. Soil suction is the attraction that soil exerts on the water has been known to increase soil stability by increasing the effective stress in soils (Nearing et al., 1988). According to Lehrsch and others (1988) soil drying increases soil cementation through the precipitation of calcium carbonates, gypsum, silica, and iron oxides.

Few studies have been conducted on actual rates of subaerial erosion. Thorne and Lewin (1979) performed a study on the banks of the upper River Severn, suggesting that subaerial activity may account for 15-20 mm/year of erosion on the cohesive upper portions of the banks, while fluvial erosion caused approximately 28 mm/year of erosion.

Lawler (1986) studied the effects of SAP on fluvial entrainment by measuring stream bank retreat for two years along two meander bends in South Wales. He established the statistical significance of frost action which loosened the soil on the surface as a preparatory process. Another study performed by Lawler (1993a) on the River Ilston, West Glamorgan, UK, deduced that erosion by needle ice accounted for sediment yields of 32 to 43 percent of the 0.15 meters of erosion recorded over a two year study. Prosser and others (2000) measured bank retreat rates of 13 mm/year on the banks of an ephemeral gully with cohesive soils in Ripple Creek canal, Tasmania, Australia. They demonstrated that the layers of loose soils (*e.g.* dried during the summer season or filled with the formation of needle ice in the winter season) easily eroded, while the underlying clay not affected by the SAP was more resistant to erosion by flowing water. Research conducted by Couper and Maddock (2001) on bank erosion on the River Arrow, Warwickshire, UK showed that the first 15 months of erosion was caused by subaerial processes, which accounted for as much as 181 mm/year of bank retreat. They state that subaerial processes are preparatory as well as erosive processes.

Fluvial Entrainment

Fluvial entrainment causes bank retreat in two ways. First is the direct removal of soil particles from the stream bank by the movement of water and second the flow of water may scour the bed and the base of the bank (Thorne, 1982; Ritter et al., 1995). According to Allen and others 1999, the erodibility of noncohesive soils is a function of soil grain size distribution, shape, and density. In contrast, particle detachment for cohesive soils is considerably more complex and is related to various soil properties and test conditions (Grissinger, 1982). There are many soil parameters that influence the susceptibility of a cohesive soil to erosion, including grain size distribution, soil bulk density or void ratio, clay type and organic matter content, and pore water content and chemistry (Grissinger, 1982; Osman and Thorne; 1988 Thorne, 1990; Allen et al., 1999, Knapen et al., 2006). Test conditions include the physical and chemical quality of the eroding water, antecedent water content, rate of wetting, and various time controls (Grissinger, 1982). Much of the literature recognizes that soil moisture is an important factor when studying soil erosion (McQueen, 1961; Grissinger et al., 1981a; Adams and Hanks, 1963; Flaxman, 1963; Enger et al., 1968; Wischmeier and Mannering, 1968; Grissinger, 1982; Thorne, 1982; Partheniades, 1986). Research indicates that bulk density is closely related to the soil stability (Grissinger, 1966; Lyle and Smerdon, 1964; Wischmeire and Mannering, 1968). Paaswell (1973) suggests that the higher the bulk density, the greater the physical particle attraction, which results in a more stable soil. Dunn (1959) related the erodibility of a soil to the plasticity index, demonstrating that as the plasticity index increases, so does the resistance to erosion. According to Hanson (1991), soils with a plasticity index less than 10 are commonly classified as cohesionless. Paaswell (1973) proposes that the plasticity index operates as a function to indicate the soils susceptiblity to erosion. According to Couper (2003), soils with high silt-clay content are more affected by SAP, which make the soils less resistant to erosion by hydraulic forces. Conversely, other studies have shown that soils with higher silt-clay content are more resistant to entrainment (Thorne and Tovey, 1981; Osman and Thorne, 1988).

Cohesive soils are based of soil structure, the interface of the soil pore water, and the eroding fluid (Heinzen, 1976), which affect the erosion of cohesive soils into entire aggregates or peds. Wynn (2004), states that the process of aggregate breakdown creates smaller particles which are more subject to erosion. The aggregate stability is influenced by soil texture, clay mineralogy, organic mater content, type and concentration of cations, and soils sesquioxide and calcium carbonate content.

Mass Wasting

Mass wasting occurs when the weight of the bank is greater than the shear strength of the soil (Osman and Thorne, 1988). It often results from increase in bank height or bank angle due to fluvial erosion and the presence of tension cracks (Simon et al., 2000). Mass wasting depends on bank geometry and straitigraphy, properties of the bank materials, the type and density of bank vegetation, percent saturation, and pore-fluid pressure (Thorne, 1990; Abernethy and Rutherfurd, 1998).

Testing Methods

The various soil properties that determine the erodibility of a soil make the prediction of soil erodibility complex (Lyle and Smerdon, 1965). There are many testing techniques utilized to evaluate soil erodibility in laboratory and field studies including: pin holes erosion devices, straight and circular flumes, rotating cylinders, and disks impellers (Allen et al., 1997). The Universal Soil Loss Equation (USLE) Haan et al., 1994) was developed for sheet and rill erosion and expresses soil erodibility as a parameter called the K factor. The K factor was developed as an integration of the impacts of rain, runoff, and soil texture (Haan et al., 1994). According to Laflen and others (1991), rill erosion and the critical hydraulic shear values did not correlate with the USLE soil erodibility K values.

Flumes have been used in various studies to determine the erodibility of soils (Smerdon and Beasley, 1961; Lyle and Smerdon, 1965, Partheniades, 1986; Heinzen, 1976). There are concerns with the use of flumes to study the erodibility of soil because the soil is typically disturbed prior to testing. In addition the integrity of the soil stability is compromised when the sample is placed into the flume. Another disadvantage of flume studies is that they use a lot of water. It may take several days to prepare the sample for testing in a flume (Grissinger, 1982).

Moore and Masch (1962) used a rotating cylinder to determine the factors that control the erosion resistance of cohesive soils. This technique disturbs to soils before testing due to the remolding process required for the samples to fit into the testing apparatus. This process affects the results by altering the surface morphology (Grissinger, 1981b).

There are other influences that must be considered when measuring stream bank erosion, such as velocities, tractive forces, and erodibility of material. In channel design, dimensions must be established based upon acceptable velocities, which allows for maximum flow without degradation to the channel (Thorne, 1982). Stream bank erosion rates in an open channel are frequently modeled using the excess stress equation:

$$E_r = Kd(\tau - \tau_c)^a$$

where *Er* is the erosion rate (m/s); *Kd* is the erodibility coefficient (m^3/N-s); τ is the applied shear stress (Pa); τ_c is the critical shear stress (Pa); and a is as exponent typically assumed to equal 1 (Hanson and Simon, 2001). The erodibility coefficient and the critical shear stress can be considered a soil property that can be used to compare relative erodibility and used in soil classification and design purposes (Heinzen, 1976; Hanson, 1990a; ASTM, 1999). The submerged, vertical jet device is an *in situ* testing procedure developed by Hanson (1989; 1990a; 1990b; 1991) to determine Kd and τ_c of channel beds. A non-vertical device for testing stream bank material has been created in cooperation with the USDA Sedimentation Laboratory in Oxford, MS (Hanson et al., 2002).

Goals and Objectives

The goal of this research was to assess the application of the submerged jet test to predict erosion of cohesive stream banks in the Blackland Prairie of North Central Texas. The results of this research will provide the information needed to properly assess the potential erosion rates along channels in watersheds undergoing urbanization and the factors that contribute to channel erosion. Specific objectives include the following:

1. Determine the rates of stream bank erosion as a function of channel dimensions (width, depth, roughness), drainage area, and slope;

2. Use *in situ* flow measurements to calibrate reach hydraulics and hydrology within each sub-basin and study reach;

3. Apply the field and laboratory measurements to a model to predict channel stream bank retreat;

4. Examine how lab estimates of erodibility coupled with cumulative flow duration and tractive force will predict field erosion rates.

Study Area

Location

The western portion of Cedar Creek watershed, located in Rockwall County and Kaufman Counties (Figure 1) contains approximately 555 square miles, which includes the urbanizing cities of Rockwall, McLendom-Chisolm, Terrell, Talty, Oak Ridge, Post Oak Bend City, Kaufman, Oak Grove, and Kemp. The western portion of Cedar Creek watershed is situated approximately 20 miles to the east from the city of Dallas, Texas. The study basin is located within the Tarrant Regional Water District (TRWD), and is one of the largest raw water suppliers in Texas, serving about 1.6 million people in ten counties in the Dallas/Fort Worth area and its surroundings. Due to the growing urbanization, the District is expected to serve a projected population of 2.66 million in 2050.

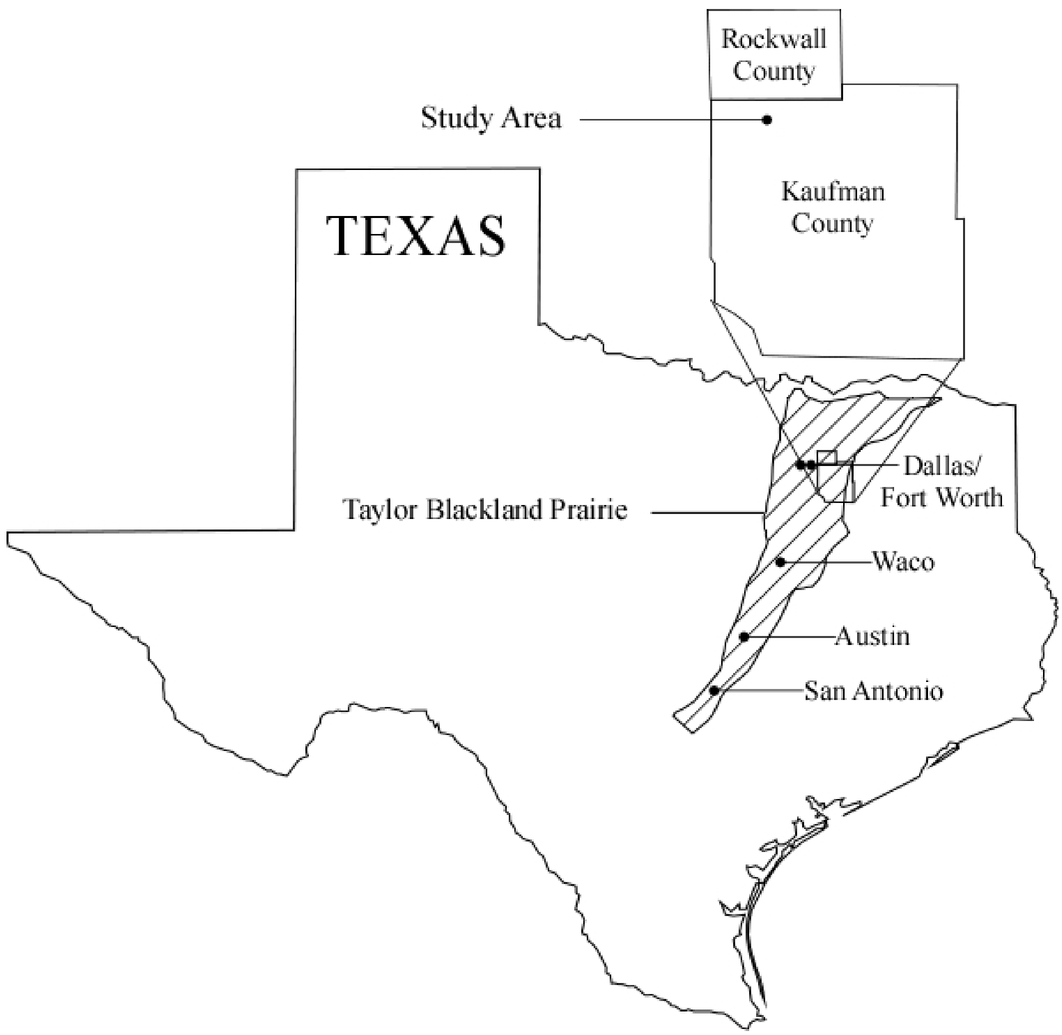


Figure 1. A map showing the position of the study area located in Rockwall and Kaufman Counties within the Blackland Prairie.

Physiography

The watershed is located within the Trinity River Basin (Figure 2), which is bordered to the west and southwest by the Brazos River Basin. The watershed lies in the Blackland Prairie physiographic province and is characterized by rolling terrain with elevation ranging from 300 to 550 feet (Figure 3). The Blackland Prairie is an approximately 80-kilometer wide, north-south trending belt spanning Central Texas from north of San Antonio to the Red River, in North Texas (Flawn and Burket, 1965).

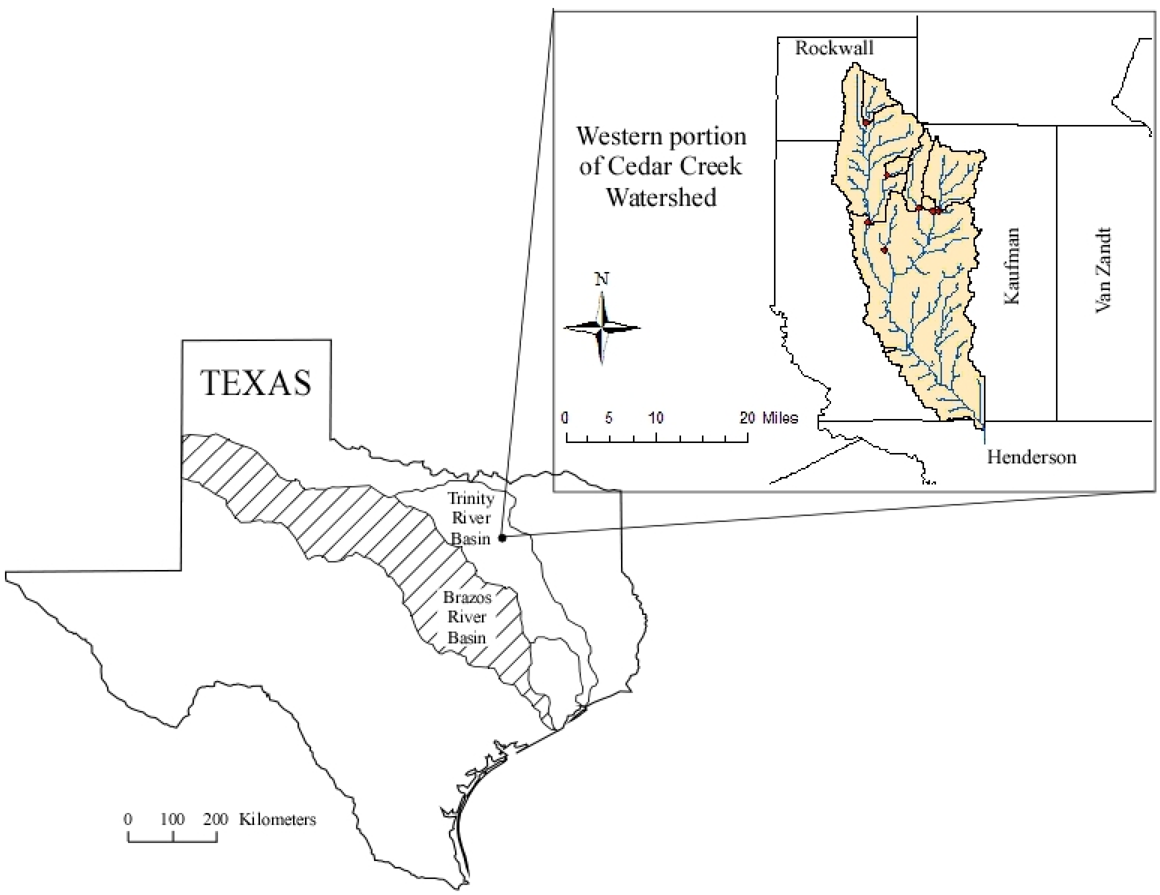


Figure 2. Map showing location of the study area of the western portion of Cedar Creek watershed located within the Trinity River basin. The Trinity River basin is bordered to the west, southwest by the Brazos River basin.

Figure 3. The illustration shows the location of the western portion of Cedar Creek Watershed on the physiographic map of Texas. Adapted from Bureau of Economic Geology, Austin, Texas (1996).

Geology and Soils

The Blackland Prairie region is underlain by Upper Cretaceous shales and limestones of the Eagle Ford, Austin Chalk, and Taylor Marl (Flawn and Burket, 1965). The watershed is underlain by the calcareous clays and marls of the Marlbrook Marl Formation, Neylandville Formation, and the Kemp Clay from youngest to oldest in age (Figure 4). A large percent of the soils in the study area consist of moderately deep to deep clayey prairie soils that are slightly alkaline, with dark to light loamy surfaces and clayey subsoils (Figure 5). The western half of the study watershed has moderate to poorly drained soils. The soils are thick and have high percentages of clay sized particles, which contribute to their cohesive nature. These clays shrink and swell upon wetting and drying cycles. The east-southeastern half of the study watershed has well to moderately drained soils. The soils vary from clay to loamy alluvium having moderate to very high shrink swell potential. All clays in the watershed have rooting depths ranging from 0-1.5 meters. The soils saturated hydraulic conductivity range from 0.2-9.0 μm/sec from the west to east within the watershed. The western portion of Cedar Creek watershed is largely open cropland and rangeland. The riparian vegetation associated with the streams consists of several species of perennial and annual shrubs as well as woody vegetation dominated by American elm (*Ulmus americana*), Texas ash (*Fraxinus texensis*), cedar elm (*Ulmus crassifolia*), juniper (*Juniperus ashei*), and Pecan (*Carya illinoensis*).

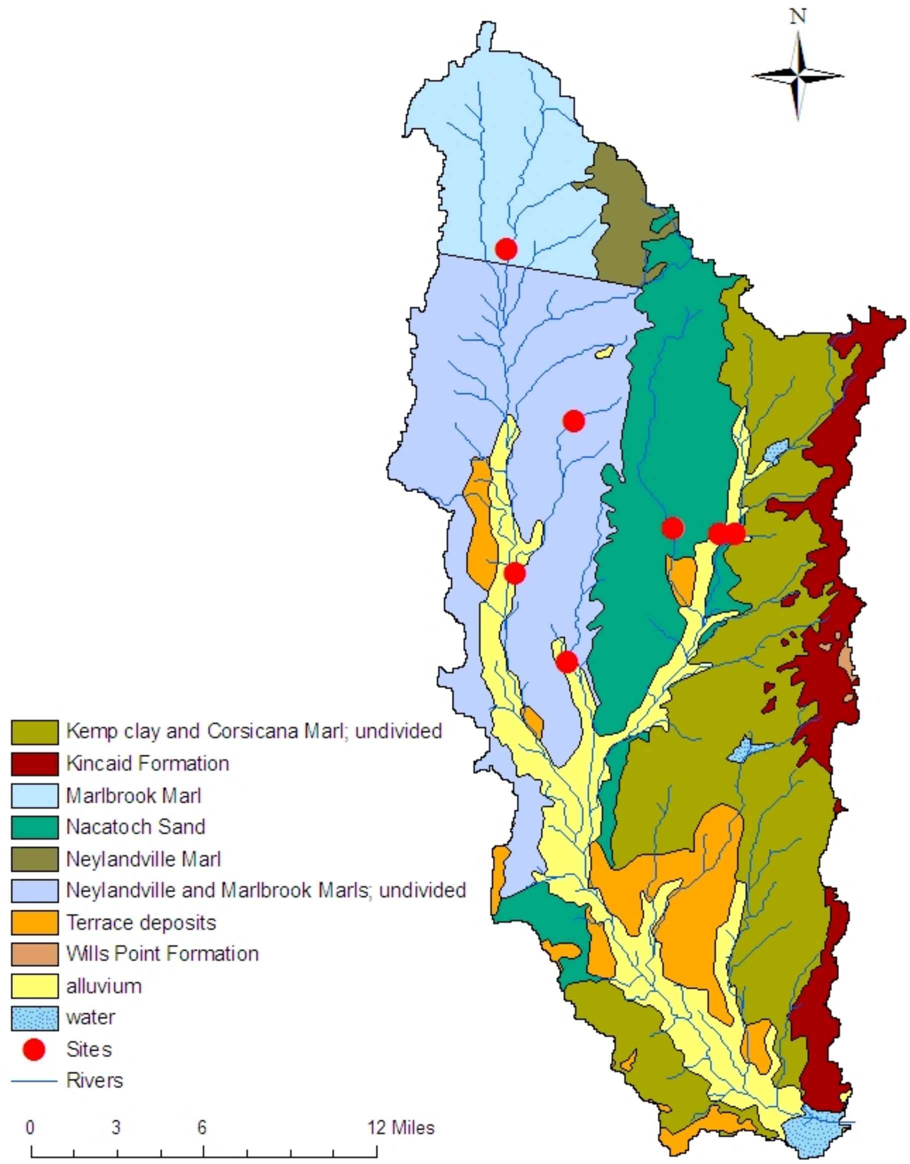


Figure 4. Geology of the western portion of Cedar Creek watershed, showing the distribution of the formations of the Upper Cretaceous, Upper Taylor Marl Group, study site locations, and rivers.

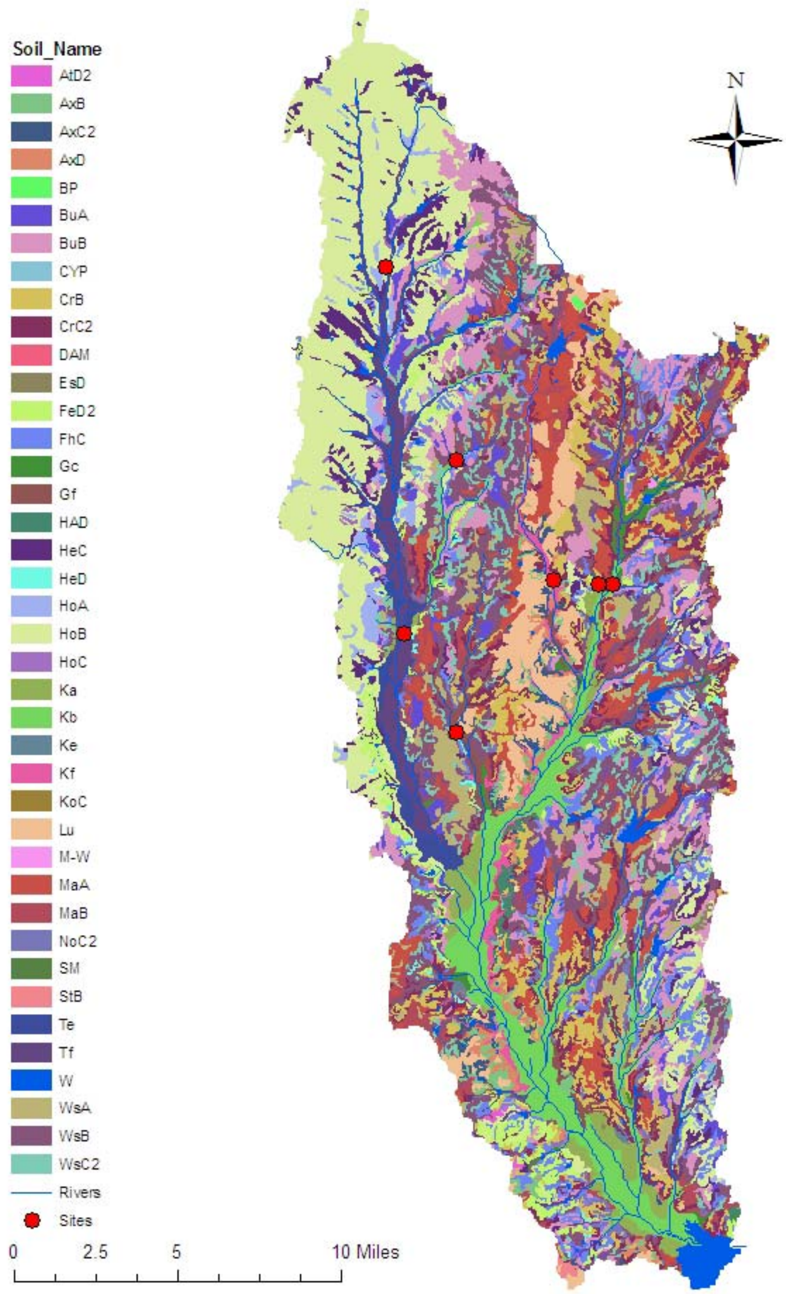


Figure 5. Surface soils map of the western portion of the Cedar Creek watershed with the study site locations and the rivers. Soils are from SURGO. Dominant soils are the Houston Black, Trinity Clay, and Kaufman Clay.

Hydrology

The Trinity is the most populated river basin in Texas with over 5.5 million residences. The 824 kilometer river and its 3190 kilometers of major tributaries drain an area of over 4.65 million hectares (Texas A&M, IRNR, 2007). Cedar Creek basin drains into the Cedar Creek reservoir, which has a conservation capacity of 838 million cubic meters and is location downstream of the proposed study location. The climate is subtropical-humid. Temperatures range in July from an average low of 22° C to an average high of 36° C and in January from 0.6° to 12° C. Rainfall averages 988 mm, and the growing season averages 245 days each year (Figure 6).

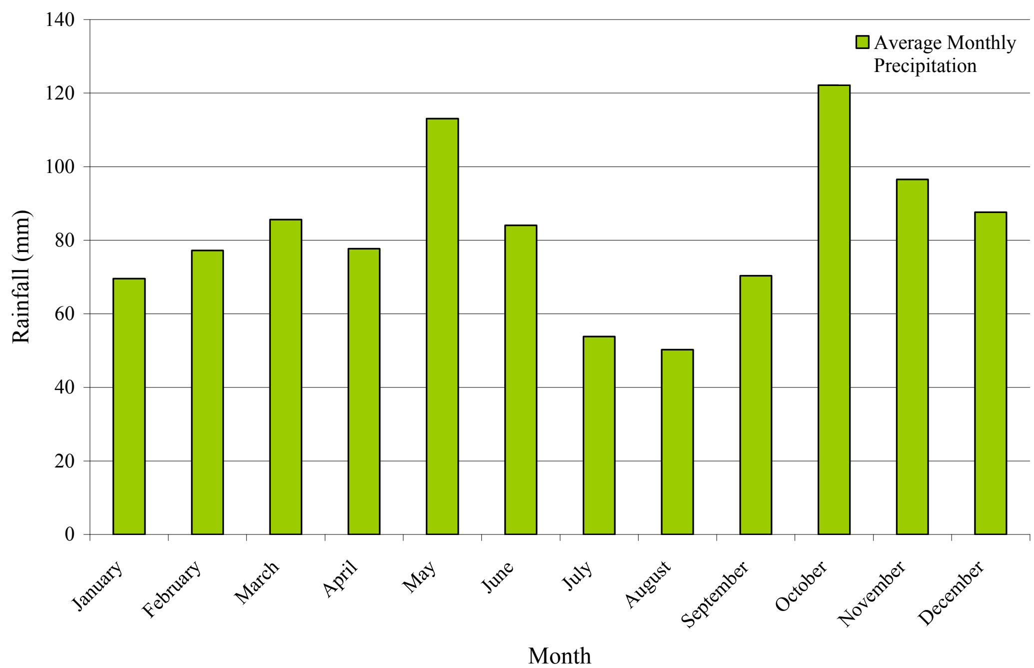


Figure 6. The graph illustrates the average monthly precipitation for Kaufman County, Texas. Source: NOAA North Central Texas Climatology.

CHAPTER TWO

Methodology

Seven field sites were established within the western portion of Cedar Creek watershed; an urbanizing area with severely eroding stream banks near urbanizing areas within. Each field site consists of a 1st to 4th order (Strahler, 1957) incised stream reach with banks 0.9-4.8 meters tall and bank angles of 54º to 90º, on private farms in Rockwall and Kaufman Counties, Texas (Figure 7). The study focused on approximately 6 meter sections on the stream bank wall within drainage areas ranging from 5-239 square kilometers. Low flow of base flow water levels varied from 10.2-91.5 centimeters with base flow channel widths ranging from 1.2-10.0 meters. Bed and bank materials ranged from clays to loamy clays in the bank and gravel over compacted clays in the channel bottom. Each study site was located in an area of no vegetation, on the outside of a meander bend, and in an area without livestock disturbance.

Channel and reach dimensions were measured with a line tape to obtain cross sectional area, channel width, depth, and thalweg slopes (Harrelson, 1994; and Rosgen, 1996). The dimensions were plotted to determine bankfull dimensions to establish the placement of erosion pins (Allen and Narramore, 1985; Dunne and Leopold, 1972).

Erosion at each site was monitored using erosion pins (Wolman, 1959; Haigh, 1977; Hooke, 1980; Thorne and Tovey, 1981; Lawler, 1993; Couper and Maddock, 2001; Couper et al., 2002; and Zaimes et al. 2005). Erosion pins are steel rods, 76 centimeters long and 1.3 centimeters in diameter, inserted perpendicular into the bank wall (Zaimes et al., 2005). Pins were inserted into the stream bank with minimal disturbance to surrounding soil and were left with 30 millimeters exposed to aid in relocation (Couper and Maddock, 2001). Only severely eroding stream banks were chosen to assess maximum potential erosion loss rates for the erosion pin grids, since these sites supply the majority of the sediment into the channel (Zaimes et al., 2005). A severely eroding bank includes: bare with slumps, vegetative overhangs and/or exposed tree roots (USDA-NRCS, 1998). The erosion pins were placed in a grid formation of five columns with 1 meter spacing (Figure 8), at two rows at one-third and two-thirds the stream bank height, apart (Figure 9) (Zaimes et al., 2005). Over the 12 month monitoring period the exposed pins were measured against the 30 mm reference datum using digital Vernier calipers (Couper and Maddock, 2001) after each storm event.

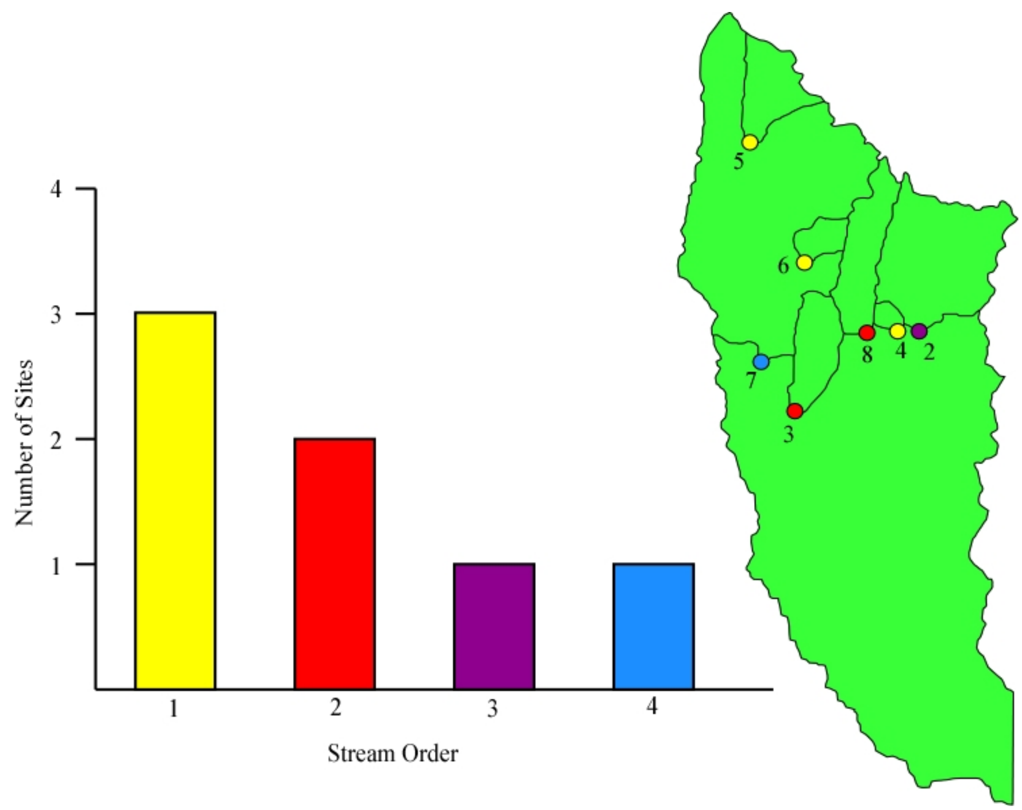


Figure 7. The figure shows a graph illustrating the proportion of the number of sites per stream order and map with the site position in the study basin of the western portion of Cedar Creek Watershed. Site 1 is not shown, due to loss of site from the development of a subdivision.

Figure 8. Photograph of the upper and lower bank erosion pin locations shown in yellow, spaced 1 m apart after Zaimes et al. 2005.

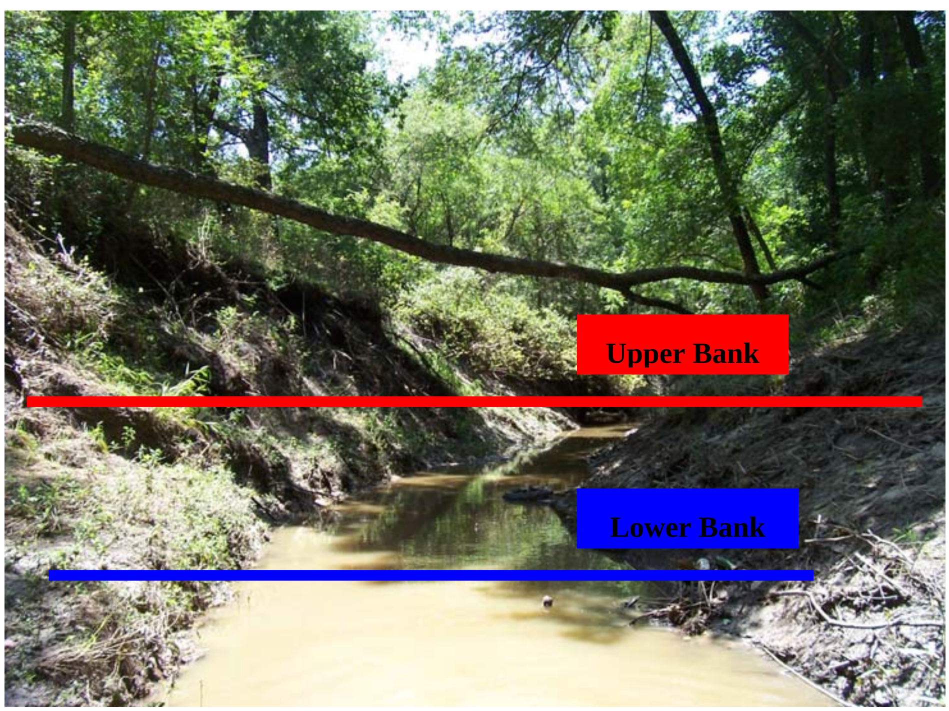


Figure 9. Photograph looking downstream at Site 2, with a drainage area of 90 km^2, illustrates the upper and lower bank positions within the stream channel.

Soil samples were collected on the stream bank wall at the same locations as the erosion pins. To determine the soil bulk density, samples were collected with an undisturbed soil core with know dimensions made of an aluminum core tube. The bulk density was obtained after the soil samples were weighed after drying for 1 day at 105 ºC (Blake and Hartge, 1986). Atterberg limits were measured in compliance with the American Standard for Testing Material (ASTM) D 4318 to obtain the liquid limit and plastic limit of the soils. The particle size distribution was analyzed using a laser particle size analyzer to obtain the percent fines of the soil (Malvern Mastersizer, 1994). Soil samples were air-dried prior to testing and processed with a soil splitter to get a representative sample. Approximately five grams of the dried soil was placed into a vial containing 45 ml of deionized water and sodium metahexaphosphate. This was added to the soil slurry to breakup any clay particles without damaging the grains. Samples were soaked for 48 hours before subject to analysis.

Hobo® Water Level Loggers were employed near to the stream bank walls being studied. The logger was placed inside a 3.8 by 17.8 centimeter polyvinyl chloride (PVC) protective tube with predrilled holes to allow water flow, and then placed inside nylon mesh to keep the fine sediment out. One level logger was utilized at each site to monitor the flow durations and hydrographs in order to assess scour durations that occurred at the upper and lower erosion pins over the course of the study.

To evaluate stream bank erodibility, the upper and lower banks at each site were tested with the submerged jet test modified after Hanson (1990b) and Allen et al. (1997). Soil samples were collected in the field by the use of steel tube with 6.35 mm thick walls and 20.3 cm in diameter and 20.3 cm long, with pneumatic extraction (figure 10). The soil was easily extracted from the sampler with little disturbance to obtain representative *in situ* samples. After extraction, samples were carefully prepared for transportation back to the lab for testing (Figure 11).

Figure 10. Photograph of the 20.3 x 20.3 cm, 6.35 mm steel tube with pneumatic extraction being placed on the upper bank to collect a soil sample for laboratory for submerged jet testing.

Figure 11. Photograph of the 20.3 x 20.3 cm, 6.35 mm steel tube with pneumatic extraction next to an extracted soil sample, being carefully prepared for transport back to the laboratory for submerged jet testing

The jet test device is shown in Figure 12. The device consists of water tanks to supply pressure to the jet test with valves to vary the jet water velocity, allowing three different soil samples to be processed simultaneously. To attain distances of scour depths, the jet was stopped at ten minute intervals and a point gage tip with the same diameter as the nozzle was used to make the measurement. Tests were conducted with water that was recycled though the system with a varying conductivity between 400 – 600 μS/cm. Each soil sample was run at a different head setting, with the head settings ranging from 38.74 – 64.14 centimeters, which corresponds to a jet velocity of 2.75 to 3.55 m/s. Results from the jet test produced a single erodibility coefficient.

The relationship between the erodibility coefficient (k) and the scour created by the submerged jet test was based on the following jet index equation (Hanson, 1990a):

$$k = 0.003e^{385 J_i}$$

where k is erodibility coefficient; and J_i is the jet index. The jet index is a function of the depth of scour hole produced by the jet on the soil surface per unit time. The jet index is determined by a least squares fit of the velocity and scour depth following the procedures outlined in ASTM 5852-95.

This study used the plasticity index to calculate the critical shear stress based on the following empirical equation (Smerdon and Beasley, 1961):

$$\tau_c = 0.16(I_w)^{0.84}$$

where τ_c is critical shear stress (Pa) and I_w is the plastic index. The critical shear stress is the stress at which soil detachment begins. If the critical shear stress is higher than the applied shear stress on the soil boundary, the erosion rate is zero (Osman and Thorne, 1988; Nearing et al., 1989; Hanson, 1990a; Hanson et al., 2002).

Figure 12. Photograph of the in-lab submerged jet test device (modified by Allen, Capello, and Coffman) during testing of three soil cores from the study area.

CHAPTER THREE

Results

The drainage areas ranged from 5 to 239 square kilometers. The watershed slope gradients range from 0.0020 to 0.0080. Water surface slopes were calculated after the first storm event, varying from 0.0030 to 0.0085. Bankfull heights and top of bank heights ranged from 0.5 to 2.3 m and 1.2 to 4.9 m, respectively. All study sites were located on the outside of meander bends with measured radius of curvatures ranging from 3.7 to 54.9 m (Table 1).

Table 1. Summary of physiographic characteristics.

Site	4	6	5	3	8	2	7
Drainage Area (sq. km.)	5	11	32	40	41	90	239
Watershed Slope (m/m)	0.0080	0.0026	0.0035	0.0020	0.0020	0.0026	0.0020
Water Surface Slope (m/m)	0.0085	0.0030	0.0040	0.0035	0.0035	0.0038	0.0040
Bankfull Height (m)	0.9	0.5	1.5	1.5	0.9	1.5	2.3
Top of Bank Height (m)	2.4	1.2	2.7	3.0	2.7	4.0	4.9
Radius of Curvature (m)	12.2	3.7	40	30.5	30.5	21.3	54.9
Bankfull Width (m)	5.5	1.8	7.3	5.8	7.6	7.9	13.7

The stream bank soils ranged from organic clay to a silty loam. Bulk densities ranged from 1.32 to 1.51 g/cm^3 for the lower bank and 1.27 to 1.57 g/cm^3 for the upper bank. The lower bank and upper bank soils generally had high plasticity indices ranging from 14 to 54. The percent clay varied from 2.34 to 24.44 in the lower bank and ranged from 1.82 to 17.32 in the upper bank (Table 2). According to Hanson's (1991) definition of cohesive soils (plasticity index greater than 10), all soil samples were considered cohesive. In general, the soils tested at all sits show similar geotechnical properties

Table 2. Summary of stream bank properties.

Site	4	6	5	3	8	2	7
Drainage Area (sq. km.)	5	11	32	40	41	90	239
Lower Bank Bulk Density (gm/cc)	1.50	1.51	1.42	1.50	1.32	1.36	1.34
Upper Bank Bulk Density (gm/cc)	1.57	1.54	1.40	1.55	1.27	1.40	1.38
Lower Bank Percent Clay[a]	10.97	x	24.44	9.39	2.34	20.34	23.44
Upper Bank Percent Clay[a]	17.32	x	10.54	11.07	1.82	17.88	13.77
Lower Bank Plastic Index	22	53	45	21	14	54	37
Upper Bank Plastic Index	20	50	43	19	14	51	36

x Indicates no data
a Particle size measured using the Malven Mastersizer 2000 (Appendix D)

During the monitoring period (Jan. 1 – Nov. 30, 2007), rainfall rates were 40 percent greater than the average for the area (Figure 13). The study period consisted of 9 to 10 storm events. Based on safety protocol (water levels and stream velocities) the erosion pin losses were measured and the water level loggers were downloaded three times and are termed as three separate *monitoring events*. The flood recurrence intervals were calculated for each event and each subbasin using peak discharges at each site calculated for each monitoring event (Table 3).

Analysis of the water level loggers permitted calculation of the durations when flow of water was at the studied pin heights for lower and upper bank (Figure 14). This was termed the *wetting duration*. The wetting duration was then tabulated for each monitored event. Bank shear at water level was calculated with WinXSPRO version 3 (Hardy et al., 2005) which computes based on the surveyed bank dimensions, bank heights, water surface slopes, radius of curvatures, and side shear (Table 1). The bank loss and wetting durations were then summed at each site for the entire monitoring period (Table 4). Site 6 was removed from the study due to cattle disturbances. Cumulative wetting durations at the lower bank locations were on average 70 percent greater than those experienced at the upper bank locations (Figure 15). Cumulative bank losses were similar for watershed less than 90 square kilometers, but were 22 percent greater in the upper bank location at the larger watershed (Figure 16). The sediment loss (mm) and the flow durations (hrs) yielded a sediment loss rate (mm/hr) for the three monitored events for the lower and upper bank locations at each site (Table 5).

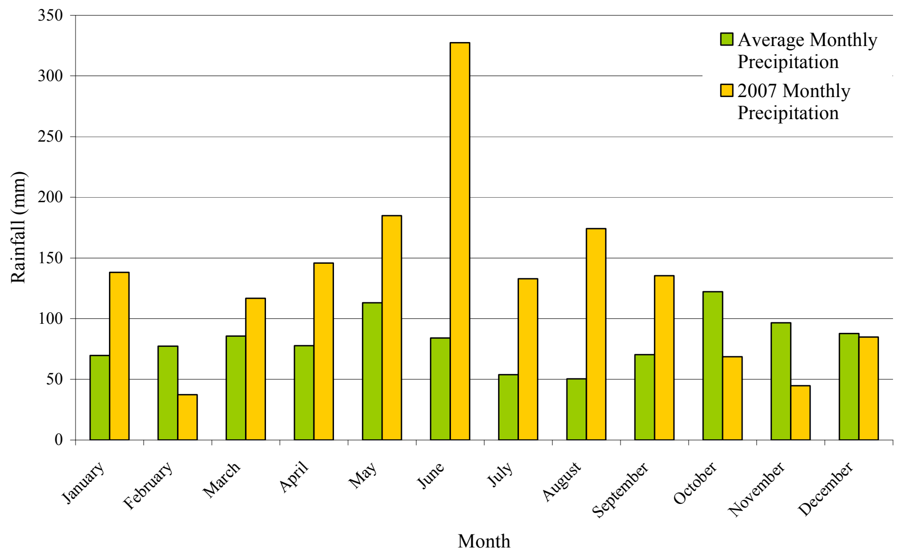


Figure 13. The graph illustrates the average monthly and 2007 monthly precipitation for Kaufman County, Texas. Source: NOAA, North Central Texas Climatology.

Table 3. Flood frequency recurrence interval of the storm events that occurred during the monitoring period.

		Recurrence Interval (year)[a]		
Drainage Area (km^2)	Site	Event 1 (Apr. – June)	Event 2 (July – Aug.)	Event 3 (Aug. – Nov.)
5	4	10	100	2
32	5	10	5	1.5
40	3	1	1.5	1
41	8	1.5	2	1.5
90	2	2	5	1.5
239	7	5	1	0.5

a All recurrence intervals are obtained from the USGS Flood Frequency Region 7 using discharges calculated using Manning's Equation (Chow, 1959).

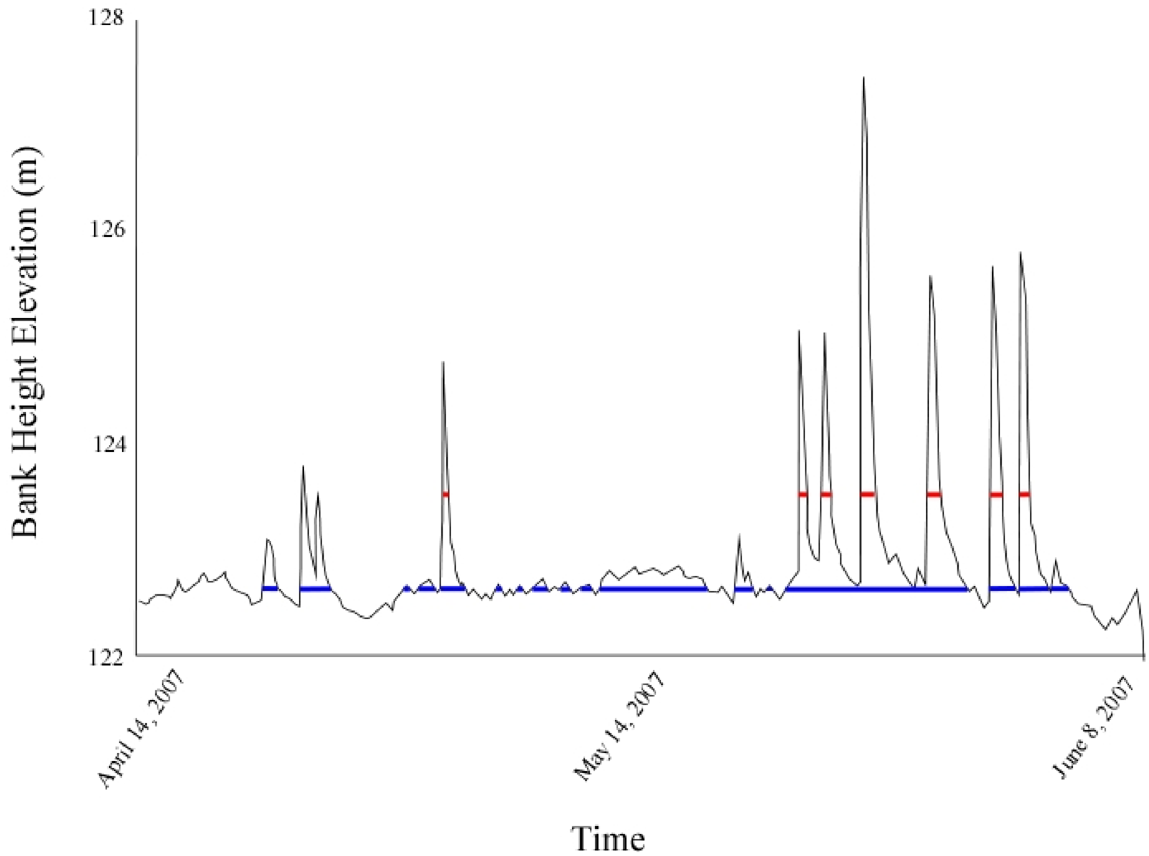


Figure 14. Hydrograph data from the HOBO® Data Logger at study site 5 for the first event monitored during April 14, 2007 through June 8, 2007. The blue line is cumulative flow duration of 230 hours and the red line is cumulative flow duration of 68 hours at the lower and upper bank locations respectively.

Table 4. Summary of lower bank and upper bank values of cumulative loss and cumulative wetting duration with respect to drainage area.

		Lower Bank Values			Upper Bank Values		
Site	Drainage Area (sq. km)	Cumulative Wetting Duration (hr)	Cumulative Loss (mm/year)	Standard Deviation (mm)	Cumulative Wetting Duration (hr)	Cumulative Loss (mm/year)	Standard Deviation (mm)
4	5	157	30.53	10.00	42	41.38	18.66
5	32	351	75.94	18.46	102	54.15	12.21
3	40	444	75.62	16.56	152	104.90	20.10
8	41	235	23.22	6.65	74	27.33	11.28
2	90	267	38.30	8.61	120	54.23	13.29
7	239	247	162.11	46.35	68	571.54	89.77

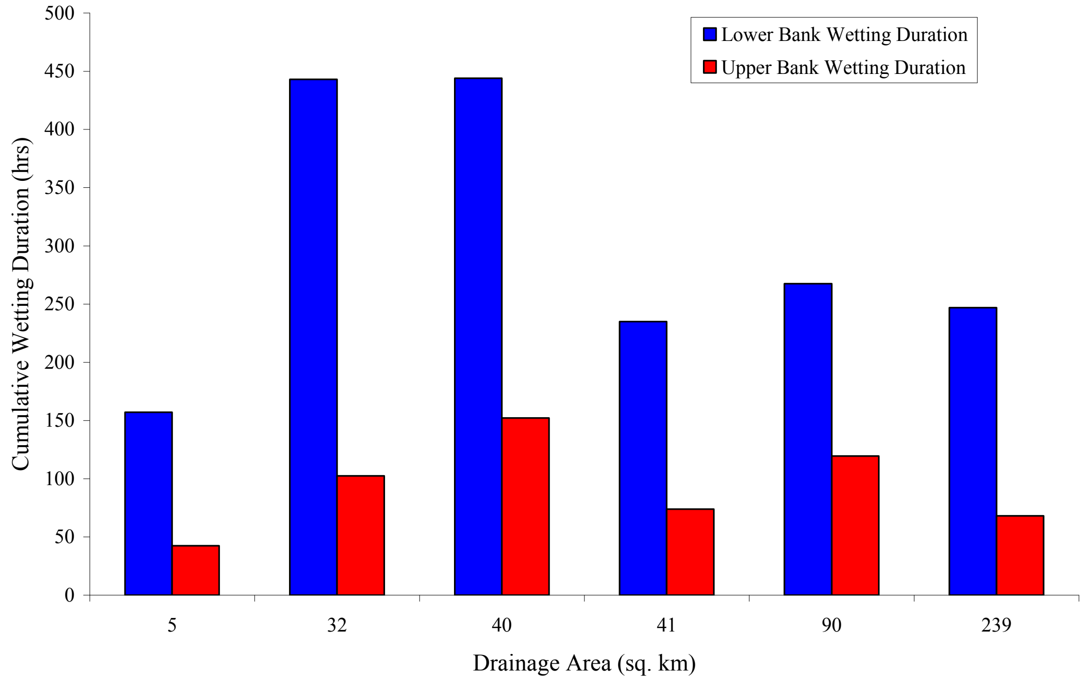


Figure 15. Cumulative wetting duration for a one year monitoring period compared to the drainage areas of the study sites. The lower bank wetting duration is on average 70 percent greater than the upper bank.

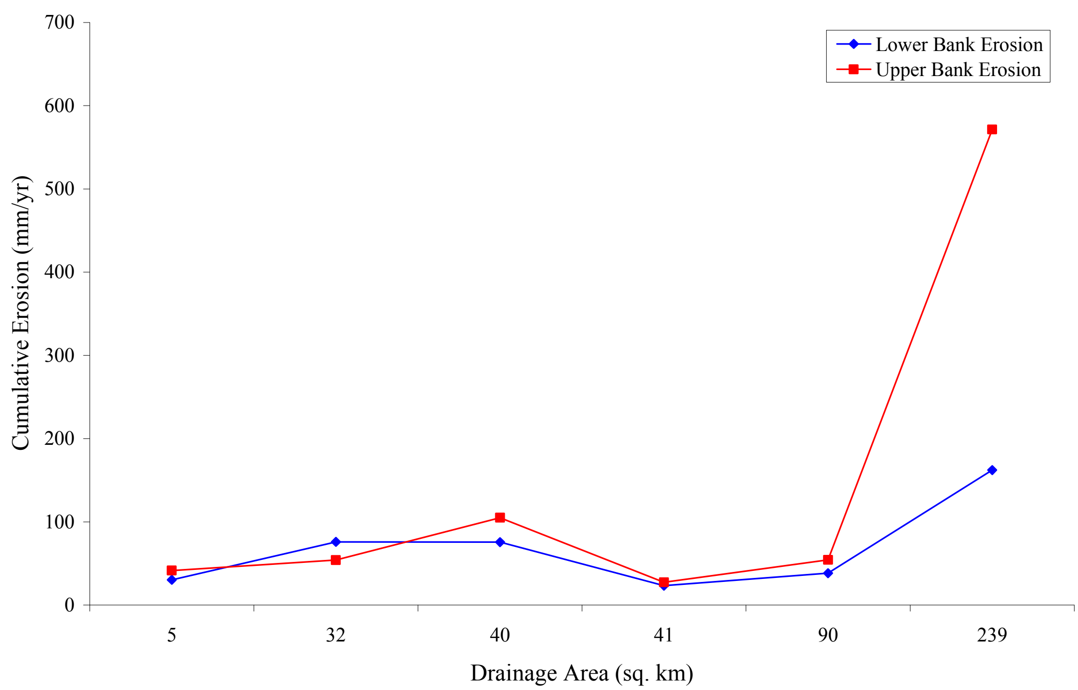


Figure 16. Cumulative erosion rate at the lower and upper bank locations for a one year monitoring period compared to the drainage areas of the study sites. The upper bank erosion rates are 22 percent greater than the lower bank in drainage areas greater than 90 square miles.

Table 5. Summary of field sediment loss rate values for three events at the lower and upper bank locations at each study site.

Site	Drainage Area	Lower Bank Values Bank Shear (Pa)	Lower Bank Values Event 1 Field Flux (mm/hr)	Lower Bank Values Event 2 Field Flux (mm/hr)	Lower Bank Values Event 3 Field Flux (mm/hr)	Upper Bank Values Bank Shear (PA)	Upper Bank Values Event 1 Field Flux (mm/hr)	Upper Bank Values Event 2 Field Flux (mm/hr)	Upper Bank Values Event 3 Field Flux (mm/hr)
4	5	15.32	0.168	0.309	0.057	18.67	0.778	1.045	3.200
5	32	16.28	0.126	0.374	0.238	32.08	0.403	0.746	1.138
3	40	12.93	0.143	0.437	0.090	33.52	0.415	1.234	1.880
8	41	24.90	0.156	0.029	0.095	43.09	0.488	0.261	0.436
2	90	22.02	0.068	0.292	0.290	41.66	0.222	0.867	1.715
7	239	37.83	0.577	0.953	0.458	72.30	2.952	26.607	31.933

Critical shear stresses were calculated with an empirical equation using the soil plasticity index (Smerdon and Beasley, 1961) (Table 6). The critical shear stresses of the stream banks were less than the applied shear stress on the soil boundary. This indicates that when the water reaches the pin height, erosion should commence. (Osman and Thorne, 1988; Nearing et al., 1989; Hanson et al., 2002, Clark and Wynn, 2007). This can be seen by comparing Table 5 and Table 6 values. The actual bank shear at the pins in five time greater than that needed to initiate detatchment.

Table 6. Summary of calculated critical shear stress.

Site	Drainage Area (sq. km)	Lower Bank Values Critical Shear Stress (Pa)[a]	Upper Bank Values Critical Shear Stress (Pa)[a]
4	5	2.15	1.98
5	32	3.92	3.77
3	40	2.06	1.90
8	41	1.47	1.47
2	90	4.56	4.35
7	239	3.32	3.25

a All critical shear stress (PA) was calculated using plasticity index and an empirical equation developed by Smerdon and Beasley (1961).

Soil samples for submerged jet testing were collected at the lower and upper bank locations at Sites 2, 4, 5, and 7. These samples were considered representative of the stream bank material throughout the watershed. The soil samples were tested with the submerged jet test device. Sites 3 and 8 were affected by backwater sediment deposition and were not included in the analysis of erosion loss.

Field erodibility values were obtained using the stream bank applied shear stress and the sediment loss rates (Table 5). Erodibility coefficients calculated using the jet indices ranged from 0.0032 to 0.0039 cm^3/N-s and from 0.0036 to 0.0042 cm^3/N-s for the lower bank and upper bank, respectively (Table 7).

Table 7. Summary of jet indices obtained from the submerged jet test and the calculated erodibility coefficient for the lower and upper banks of each site.

	Lower Bank Values		Upper Bank Values	
Site	Jet Index (Ji)	Erodibility Coefficient (k) (cm^3/N-s)	Jet Index (Ji)	Erodibility Coefficient (k) (cm^3/N-s)
2	0.0006	0.00377	0.0009	0.00423
4	0.0002	0.00323	0.0005	0.00363
5	0.0006	0.00377	0.0007	0.00392
7	0.0003	0.00336	0.0005	0.00364

Using a simple t-test the sample means are similar at the 95 percent confidence interval. The pin loss rate in cm^3/N-s were determined from assessing cumulative wetting duration, tractive force, and average erosion loss from the pins. Comparison of the pin loss rates to the jet test loss rates is shown in Tables 8a and 8b. The separate events are shown as well as the mean loss for all events and the standard deviation.

The loss rate in the lower bank is about eight times less than the upper bank for all events. The t-tests indicate that the mean loss rate for both the upper and lower bank determined from the field pin data is not statistically different from the mean loss determined by the lab jet test.

Table 8a. Summary of the erodibility values calculated for the field and compared to ASTM D5852-95 for the lower bank.

Drainage Area	Site	Erodibility Coefficient (K) (cm^3/N-s) Field Event 1	Field Event 2	Field Event 3	ASTM D5852-95	Mean of Events	Standard Deviation
5	4	0.0031	0.0056	0.0010	0.0032	0.0032	0.0023
32	5	0.0021	0.0064	0.0041	0.0039	0.0042	0.0022
90	2	0.0008	0.0037	0.0035	0.0038	0.0027	0.0016
239	7	0.0042	0.0070	0.0034	0.0039	0.0049	0.0019

Table 8b. Summary of the erodibility values calculated for the field and compared to ASTM D5852-95 for the upper bank.

Drainage Area	Site	Erodibility Coefficient (K) (cm^3/N-s) Field Event 1	Field Event 2	Field Event 3	ASTM D5852-95	Mean of Events	Standard Deviation
5	4	0.0116	0.0155	0.0476	0.0036	0.0249	0.0198
32	5	0.0035	0.0065	0.0099	0.0039	0.0066	0.0032
90	2	0.0015	0.0058	0.0114	0.0042	0.0062	0.0050
239	7	0.0113	0.1022	0.1227	0.0036	0.0787	0.0590

Predicted bank loss in millimeters was determined using the calculated erodibility coefficients (Tables 8a and 8b), applied bank shear stress, and wetting duration from the lower and upper pin locations for three monitored events from the monitoring period. The event values were then averaged and percent error was calculated using the mean event actual loss at both pin locations for each site. The percent errors were average to produce an overall mean percent error for method ASTM D5258-95 at the lower bank and upper bank locations. The ASTM D5852-95 method over-estimated lower bank loss by 30.08 percent and under-estimated upper bank loss by 34.56 percent.

CHAPTER FOUR

Discussion

Overall Erosion Rates Compared to Other Studies

Stream bank erosion rates obtained with the erosion pin method are compared on Table 9. Actual field erosion rates in cohesive soils and bank loss by subaerial erosion are seldom reported in bank erosion literature. The mean observed erosion rates on the rivers in the study area for the lower bank and upper bank are 67.59 mm/yr and 142.26 mm/yr, respectively. However maximum values reached as high as 162.11 mm/year in the lower bank and 571.54 mm/yr in the upper bank and when averaged, equal 366.82 mm/yr at Site 7. This rate is approximately between 93-96 percent higher than those rates observed by Thorne and Lewin (1979), Lawler (1993), Prosser et al. (2000), and Couper and Maddock (2001). These high bank loss rates may be attributed to site differences in soil properties, bank vegetation, or meteorological conditions. Alternatively, these higher rates could perhaps be explained by the increase of high flows in the rivers of the western portion of Cedar Creek watershed throughout the study. This allowed for a greater number of wet/dry cycles for the upper bank locations. The implications of using this method in terms of sediment loss per kilometer of channel yield rates ranging between 134 – 2681 tons/km.

Table 9. Rates of field bank retreat in streams with comparable drainage areas and cohesive soils.

Reference	Location	Drainage Area (km^2)	Erosion Rate (mm/yr)
This Study			
Lower Bank	Texas, USA	5-239	23 – 162
Upper Bank			27 – 572
Wolman (1959)	Watts Beck, Maryland, USA	9.6	450-600
Thorne and Lewin (1979)	River Severn, Wales, UK	375	15-20
Lawler (1993)	River Ilston, West Glamorgan, UK	< 15	27
Prosser et al., (2000)	Ripple Creek canal, Tasmania, Australia	46	16
Couper and Maddock, (2001)	River Arrow, Warickshire, UK	92	10-40

Jet Test Results

This study utilized a jet test device to test the submerged processes of both the lower and upper bank locations and obtain an erodibility coefficient. The range of the lower bank was from 0.0032 to 0.0039 cm^3/N-s and the upper bank was from 0.0036 to 0.0042 cm^3/N-s. The erodibility coefficients were three percent higher for the upper bank than for the lower bank, which reiterates the fact that soil parameters influence the susceptibility of a cohesive soil to erosion (Grissinger, 1982; Osman and Thorne, 1988; Thorne, 1990; Allen et al., 1999; and Couper, 2003). The lower banks have higher clay contents. Tests indicate that as the percent clay of the soil increased, the jet index decreased, resulting in decreased soil erodibility (Dunn, 1959).

This study shows that the jet index test is a viable means to predict the erodibility coefficient, which can be used to predict loss rates when coupled with either gage data of continuous simulated models such as the Soil Water Assessment Tool (SWAT). Clark and Wynn (2007) conducted jet test studies, and erodibility coefficients (k) measured from the jest test were compared to predictions from two empirical erodibility relations. The equations produced similar k values that were generally two orders of magnitude less than the values from the jet test measurements. Knapen and others (2007) suggests that most soil and environmental properties (*e.g.*, moisture content, bulk density and consolidation) seem to affect the erodibility of a soil. Field tests are necessary to obtain actual erosion rates in order to properly assess whether a laboratory test such as the jet test is a viable method to predict loss rates.

Erosion and Subaerial Processes

This study shows that erosion rates can be predicted with the use of a submerged jet test, and that the rates are a function of drainage area and channel characteristics. Drainage area is an important factor that controls water flow duration, and channel dimensions affect bank shear stress.

The lower bank was affected by water flow duration on average 70 percent more than the upper bank. Sites 3 and 5 had the highest flow durations in the lower bank, which is attributed to poorly designed culverts downstream that do not allow for proper drainage. The upper bank had on average of 22 percent greater cumulative bank loss compared to the lower bank. Site 7, with the largest drainage area of 239 km^2, had the greatest cumulative upper bank loss. This study site is located at the lower reaches of the watershed, with a baseflow channel width of 13.7 meters, bank walls heights of 4.9 meters, and non-vegetated stream bank walls.

Lawler and others (1999) have shown that erosion increases downstream within a basin (Figure 17). This is attributed to a combination of bank erosion processes. Figure 17 shows a schematic that represents a stream reach and the downstream processes that occur within each section (*e.g.* upper, middle and lower reaches). The upper reaches represent the headwaters zones, which are dominated by the weathering process known as a wash-line, where subaerially loosened sediment has been washed off by flowing water (Prosser et al., 2000). Bank heights are too low for mass failure processes (Lawler, 2004). The middle reaches are dominated by fluvial entrainment, derived from declining slopes and increasing discharges, which undercut banks and cause tension cracks (Lawler, 2004). The lower reaches are dominated mass failure processes, which are linked to fine-grained banks of large unit weight (Lawler, 2004). Mass failure processes include: detaching blocks, planar failures and collapsed blocks.

Lawler's (2004) scale-driven model shows that in larger basins, bank geometries and materials become conducive to frequent bank collapse. Lawler and others (1999) have shown, with the use of flood hydrograph base-times, that flow duration increases in the downstream direction. They suggest that the lateral uptake of water during high flow events is low and many mass failures take place well after a storm event. This explains the erosion processes that are apparent at Site 7, with a drainage area of 239 km^2, which is in the lower reaches of the watershed studied during this monitoring period. Lawler (1992, 1995) suggests that mass failure processes only become important when banks exceed critical heights at some point in the basin. Lawler (2004) shows that mass failure erosion processes become significant when a drainage area exceeds 110 km^2.

Site 7, with the largest drainage area (239 km^2), displays the processes illustrated in the lower reaches of Lawler's (2004) schematic (Figure 18). Tension cracks, planar failures, collapsed blocks were observed at Site 7, which had the largest erosion rates of 162 – 572 mm/yr.

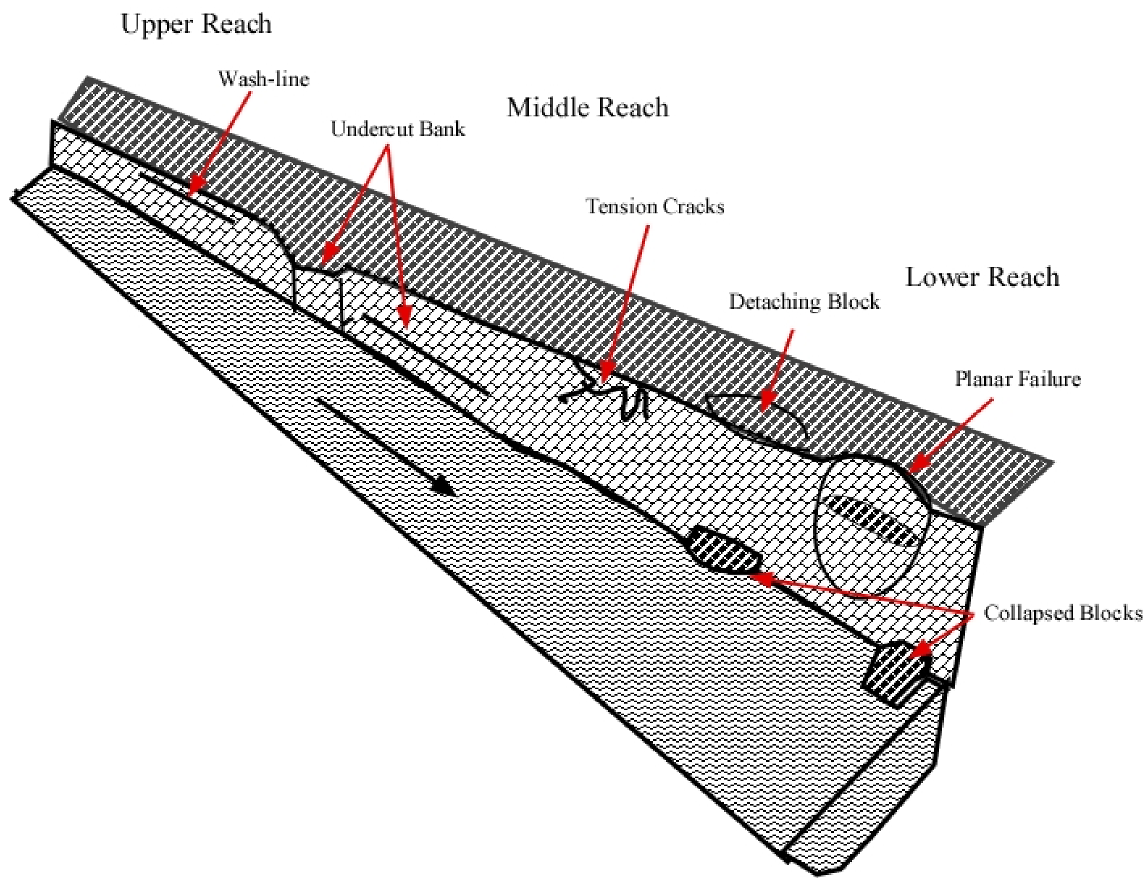


Figure 17. A schematic representation of downstream changes in dominant river bank erosion processes. Figure modified after Lawler (2004).

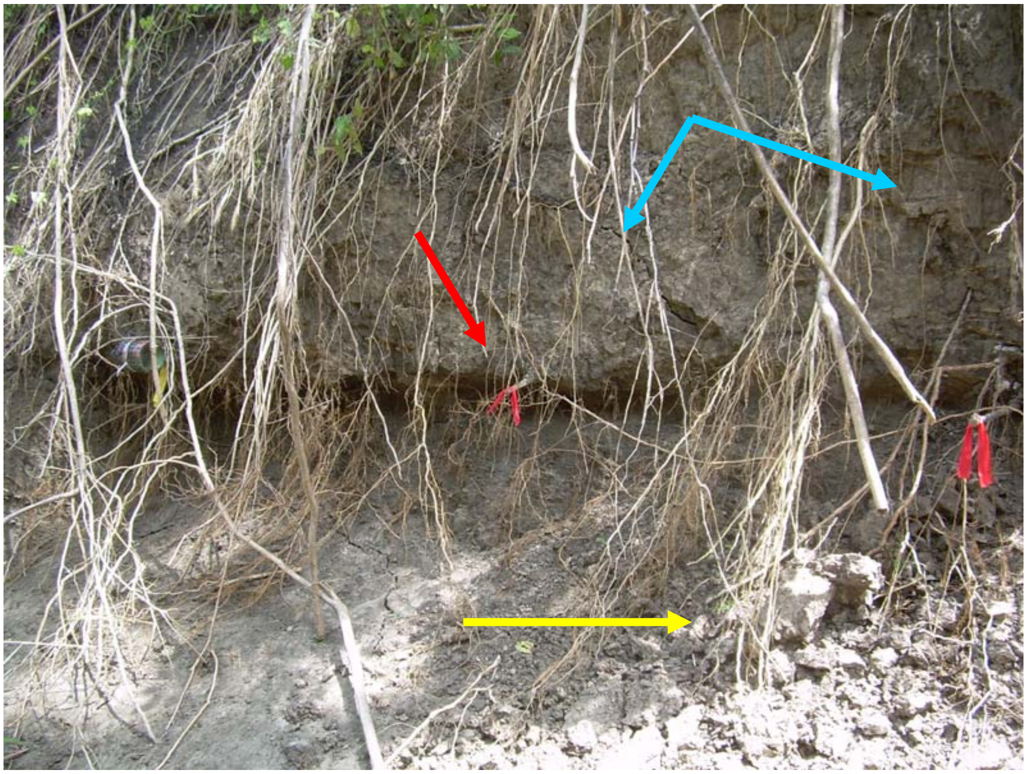


Figure 18. Photograph of the upper bank at Site 7 (drainage area 239 km^2). The erosion pins are marked with red flagging tape (red arrow) where the bank is being undercut by water flow. The photograph shows tension cracks (blue arrows) and fallen bank material (yellow arrow).

During the monitoring period tension cracks were observed that are inferred to result from soil dessication. These tension cracks reduce the structural strength of a stream bank (Thorne, 1982). Cycles of wetting and drying influence bank erodibility (Knighton, 1973), decreasing the aggregate size (Shiel et al., 1988), and make the soil more susceptible to erosion during storm events.

Lab Jet Test and Predicted Field Erosion

The data collected in the field was applied to the ASTM D5258-95 erodibility coefficients to calculate sediment loss in millimeters. This was conducted to distinguish if the submerged jet test could be used to predict stream bank retreat. Testing revealed that erodibility coefficients obtained from the ASTM D5852-95, when combined with field monitored duration and bank shear stress, correlate to measured field erosion rates (Table 8).

This research is the first to demonstrate that erosion rates can be predicted (Figure 19) by the use of a submerged jet test. This was accomplished by field *in situ* methods using erosion pins and water level loggers. Hanson (1990) performed flume studies to obtain loss rates to compare to the rates resulting from the submerged jet test (ASTM D5258-95).

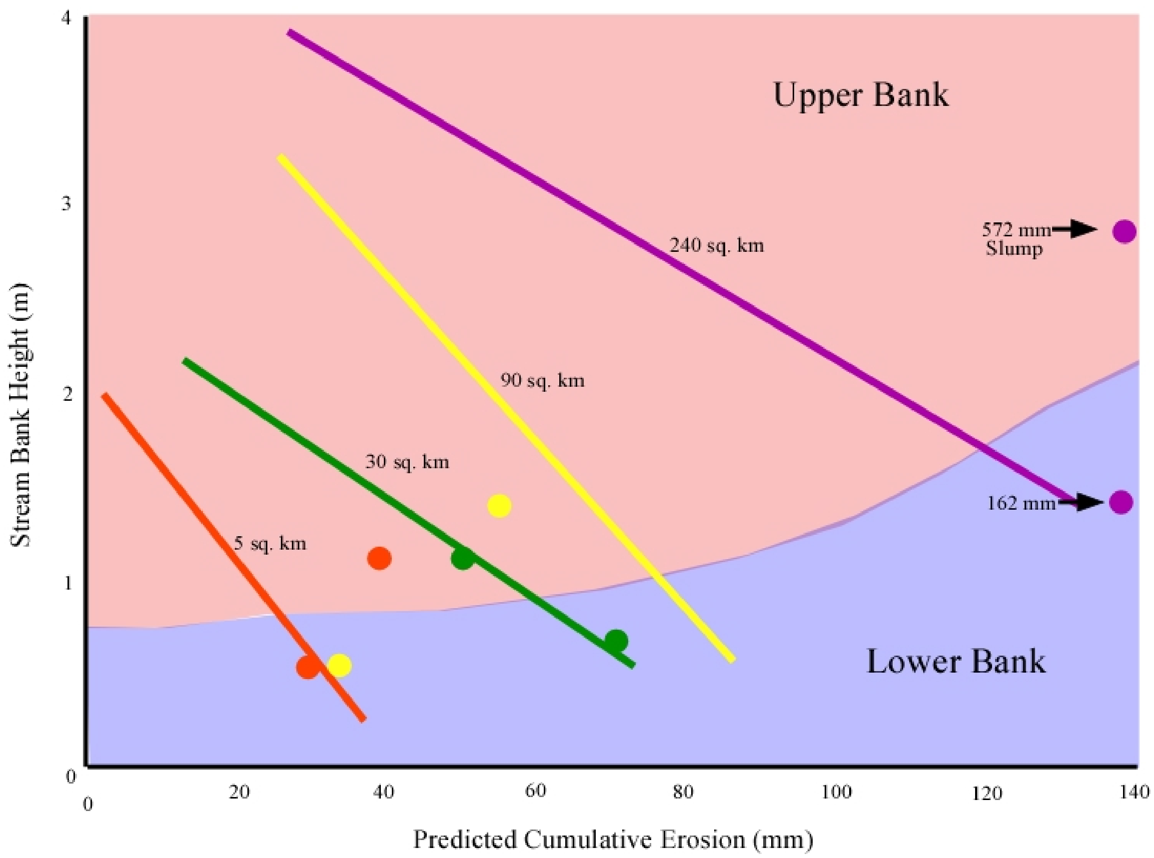


Figure 19. Diagram showing the predicted erosion obtained from the submerged jet test (lines) and the actual rates (circles).

This diagram indicates predicted erosion for the study sites based on flow duration and bank position. Each line in Figure 19 is in the form of:

$$H_b = a(Er_p) + b$$

where H_b is stream bank height; Er_p is predicted cumulative erosion; and *a* and *b* are constant values that pertain to each drainage area (Table 10). Er_p is obtained from:

$$Er_p = D_w \times K_j \times F_t$$

where D_w is wetting duration; K_j is the jet test erodibility coefficient; and F_t is tractive force (Appendix C). The field sites are represented as colored circles. Upper and lower bank levels are shown (Figure 19). For example, for a lower bank in a five square kilometer watershed, 25 to 40 mm of erosion could be expected, compared to 120 to 135 mm of erosion in a 240 square kilometer watershed. The upper bank, due to less flow duration would range from 5 to 25 mm of erosion in a five square kilometer watershed to 25 to 120 mm of erosion in a 240 square kilometer basin, respectively. The slopes of the lines for each drainage area vary due to differences in wetting duration and bank shear. The actual erosion rates are not on the predicted slope for the 90 square kilometer watershed. This is attributed to slumps and slow moving creep of the stream bank.

Table 10. Summary of constant values for the regression equation to calculate predicted cumulative erosion for each drainage area.

Drainage Area (km^2)	*a*	*b*
5	-0.164	6.314
30	-.0.077	7.785
90	-0.158	15.705
240	-0.080	15.297

CHAPTER FIVE

Conclusion

The goal of this research was to assess the application of the submerged jet test to predict erosion of cohesive stream banks in the Blackland Prairie of North Central Texas. The use *in situ* flow measurements were applied to calibrate reach hydraulics and hydrology within each sub-basin and study basin. The study quantified the causative effects of stream bank erosion of channels in areas undergoing urbanization in the Blackland Prairie. Lastly, field and laboratory measurements were applied to a model to predict stream bank retreat. From this study of bank erosion on the rivers of the western portion of Cedar Creek watershed over a one year monitoring period, four conclusions have been reached.

1. Erosion rates can be predicted by the use of a submerged jet test, which was accomplished by *in situ* methods using erosion pins and water level loggers

2. Durations obtained from water level loggers and bank shear values are a reliable way to test the validity of the submerged jet test device.

3. The predicted erosion rates show that erosive processes are a factor of both drainage area and channel dimensions, controlling the flow duration and bank shear stress, respectively.

4. When field monitoring data is not available, the ASTM D5852-95 produces results that correlate to field bank retreat rates in cohesive stream banks.

APPENDICES

APPENDIX A

GPS Locations of Field Sites

Table A.1. GPS locations for each field site.

Drainage Areas (sq.km)	Longitude	Latitude
5	-96.270047	32.699297
11	-96.343169	32.756275
32	-96.376936	32.842356
40	-96.346511	32.468603
41	-96.293183	32.701958
90	-96.262128	32.699361
239	-96.372431	32.67975

APPENDIX B

Channel Cross Sectional Data

Distance	Elevation
0	440
3	438
6	437
9	436
12	436
15	437
18	437
21	437
24	437
27	437
30	437
33	436
36	436
39	437
42	438
45	437
48	437
51	436
54	435
57	435
60	434
63	432
66	432
69	433
72	435
75	440

Figure B.1. Channel cross sectional area for Site 4 with a drainage area of 5 sq. km.

Distance	Elevation
0	411
3	410
6	408
9	407
12	407
15	408
18	407
21	404
24	403
27	402
30	402
33	402
36	403
39	405
42	407
45	409
48	411

Figure B.2. Channel cross sectional area for Site 5 with a drainage area of 32 sq. km.

Figure B.3. Channel cross sectional area for Site 3 with a drainage area of 40 sq. km.

Distance	Elevation
0	411
3	410
6	405
9	404
12	403
15	403
18	402
21	402
24	402
27	402
30	404
33	407
36	409
39	410
42	410
45	410
48	409
51	408
54	408
57	409
60	411

Figure B.4.   Channel cross sectional area for Site 8 with a drainage area of 41 sq. km.

Figure B.5. Channel cross sectional area for Site 2 with a drainage area of 90 sq. km.

Distance	Elevation
0	421
3	420
6	416
9	412
12	410
15	408
18	407
21	405
24	405
27	405
30	406
33	406
36	406
39	407
42	407
45	407
48	408
51	411
54	412
57	412
60	414
63	421
66	421

Figure B.6. Channel cross sectional area for Site 2 with a drainage area of 90 sq. km.

APPENDIX C

Predicted Cumulative Erosion Data

Table C.1. Summary of the data used to produce the predicted cumulative erosion diagram (refer to Figure 19).

Site	Bank Height (ft)	Tractive Force (psf)	Jet Erodibility Coefficient (k) (in/hr/psf)	Wetting Duration (hrs)	Predicted Cumulative Erosion (mm)
2	2	0.48	0.0256	270	84.20
	5	0.87	0.0256	120	67.60
	8	1.18	0.0256	70	53.71
	11	1.30	0.0256	32	27.05
4	2	0.32	0.0219	157	27.94
	4	0.39	0.0219	42	9.11
	5	0.45	0.0219	19	4.75
	7	0.50	0.0219	9	2.50
5	2	0.34	0.0256	351	77.60
	4	0.67	0.0256	102	46.17
	5	0.70	0.0256	62	28.22
	7	1.00	0.0256	28	18.20
7	5	0.79	0.0266	247	131.84
	7	1.08	0.0266	132	96.14
	10	1.51	0.0266	68	69.37
	13	1.80	0.0266	24	29.15

APPENDIX D

Grain Size Analysis

MALVERN

MASTERSIZER 2000

Result Analysis Report

Sample Name:
2L

Sample Source & type:
Ceder Creek

Sample bulk lot ref:

SOP Name:
Ceder Creek

Measured by:
Zhaodong Feng

Result Source:
Measurement

Measured:
Saturday, April 12, 2008 1:31:43 PM

Analysed:
Saturday, April 12, 2008 1:31:44 PM

Particle Name:
Kaolinite high

Particle RI:
1.570

Dispersant Name:
Propan-2-ol

Accessory Name:
Hydro 2000MU (A)

Absorption:
0.1

Dispersant RI:
1.390

Analysis model:
General purpose

Size range:
0.020 to 2000.000 um

Weighted Residual:
1.060 %

Sensitivity:
Enhanced

Obscuration:
18.39 %

Result Emulation:
Off

Concentration:
0.0113 %Vol

Specific Surface Area:
1.85 m^2/g

Span :
18.249

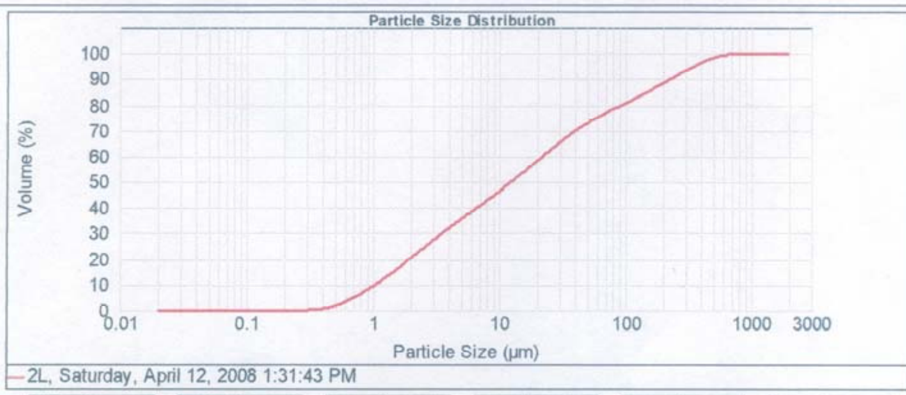
Surface Weighted Mean D[3,2]:
3.245 um

Uniformity:
5.01

Vol. Weighted Mean D[4,3]:
66.319 um

Result units:
Volume

d(0.1): 1.040 um   d(0.5): 12.479 um   d(0.9): 228.770 um



Size (µm)	Volume In %
0.010	
	20.34
2.000	
	11.72
4.000	

Size (µm)	Volume In %
4.000	
	10.57
7.800	
	11.10
15.600	

Size (µm)	Volume In %
15.600	
	12.17
31.000	
	9.77
62.500	

Size (µm)	Volume In %
62.500	
	7.28
125.000	
	8.13
250.000	

Size (µm)	Volume In %
250.000	
	7.19
500.000	
	1.73
2000.000	

Size (µm)	Volume In %
2000.000	

Malvern Instruments Ltd.
Malvern, UK

Mastersizer 2000 Ver. 5.40
Serial Number : MAL1009604

File name: Ceder Creek
Record Number: 1

Figure D.1. Grain size analysis of the lower bank at site 2.

MASTERSIZER 2000

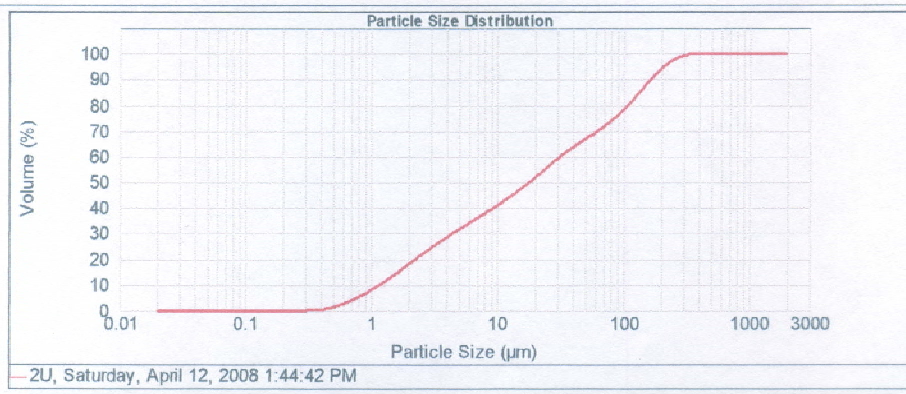
Result Analysis Report

Sample Name: 2U	**SOP Name:** Ceder Creek	**Measured:** Saturday, April 12, 2008 1:44:42 PM
Sample Source & type: Ceder Creek	**Measured by:** Zhaodong Feng	**Analysed:** Saturday, April 12, 2008 1:44:43 PM
Sample bulk lot ref:	**Result Source:** Measurement	

Particle Name: Kaolinite high	**Accessory Name:** Hydro 2000MU (A)	**Analysis model:** General purpose	**Sensitivity:** Enhanced
Particle RI: 1.570	**Absorption:** 0.1	**Size range:** 0.020 to 2000.000 um	**Obscuration:** 15.99 %
Dispersant Name: Propan-2-ol	**Dispersant RI:** 1.390	**Weighted Residual:** 0.889 %	**Result Emulation:** Off

Concentration: 0.0109 %Vol	**Span :** 8.998	**Uniformity:** 2.68	**Result units:** Volume
Specific Surface Area: 1.61 m^2/g	**Surface Weighted Mean D[3,2]:** 3.736 um	**Vol. Weighted Mean D[4,3]:** 53.798 um	

d(0.1): 1.168 um   d(0.5): 18.170 um   d(0.9): 164.662 um



Size (μm)	Volume In %
0.010	
	17.88
2.000	
	10.52
4.000	

Size (μm)	Volume In %
4.000	
	9.20
7.800	
	9.85
15.600	

Size (μm)	Volume In %
15.600	
	12.12
31.000	
	10.34
62.500	

Size (μm)	Volume In %
62.500	
	13.25
125.000	
	14.47
250.000	

Size (μm)	Volume In %
250.000	
	2.36
500.000	
	0.00
2000.000	

Size (μm)	Volume In %
2000.000	

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File name: Ceder Creek
Record Number: 2
20 May 2008 2:56:35 PM

Figure D.2. Grain size analysis of the upper bank at site 2.

MASTERSIZER 2000

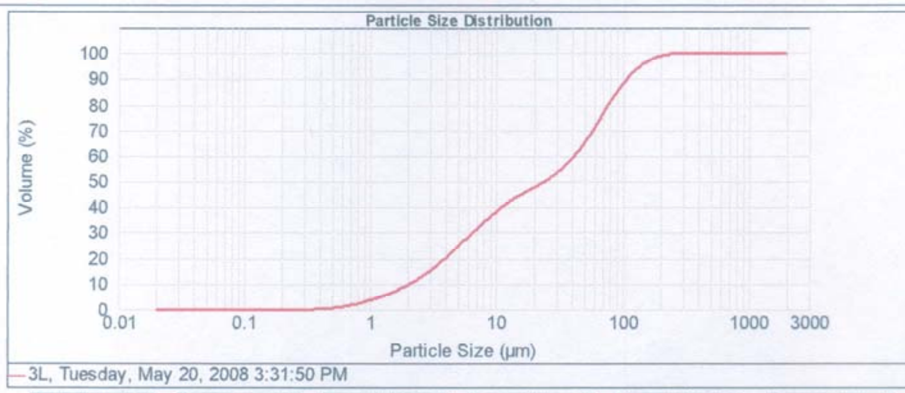
Result Analysis Report

Sample Name: 3L
SOP Name: Ceder Creek
Measured: Tuesday, May 20, 2008 3:31:50 PM
Sample Source & type: Ceder Creek
Measured by: Zhaodong Feng
Analysed: Tuesday, May 20, 2008 3:31:51 PM
Sample bulk lot ref:
Result Source: Measurement

Particle Name: Kaolinite high
Accessory Name: Hydro 2000MU (A)
Analysis model: General purpose
Sensitivity: Enhanced
Particle RI: 1.570
Absorption: 0.1
Size range: 0.020 to 2000.000 um
Obscuration: 14.64 %
Dispersant Name: Propan-2-ol
Dispersant RI: 1.390
Weighted Residual: 0.790 %
Result Emulation: Off

Concentration: 0.0135 %Vol
Span : 4.410
Uniformity: 1.48
Result units: Volume
Specific Surface Area: 1.07 m^2/g
Surface Weighted Mean D[3,2]: 5.625 um
Vol. Weighted Mean D[4,3]: 42.597 um

d(0.1): 2.110 um　　d(0.5): 24.180 um　　d(0.9): 108.732 um



Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %
0.010	9.39	4.000	13.69	15.600	9.21	62.500	20.53	250.000	0.27	2000.000	
2.000	10.68	7.800	10.87	31.000	18.77	125.000	6.59	500.000	0.00		
4.000		15.600		62.500		250.000		2000.000			

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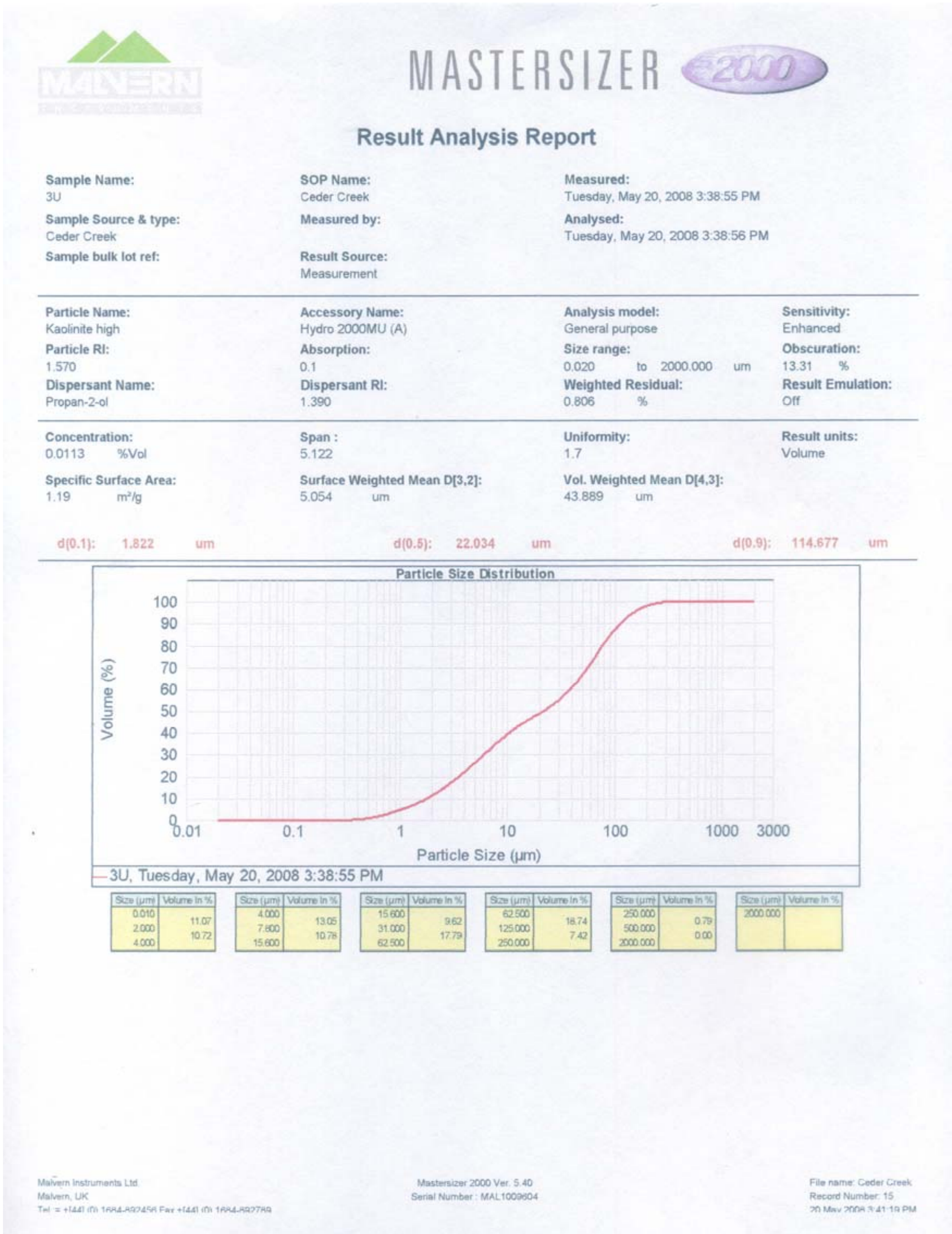
Record Number: 14
20 May 2008 3:41:13 PM

Figure D.3. Grain size analysis of the lower bank at site 3.



MASTERSIZER 2000

Result Analysis Report

Sample Name: 3U
SOP Name: Ceder Creek
Measured: Tuesday, May 20, 2008 3:38:55 PM
Sample Source & type: Ceder Creek
Measured by:
Analysed: Tuesday, May 20, 2008 3:38:56 PM
Sample bulk lot ref:
Result Source: Measurement

Particle Name: Kaolinite high
Accessory Name: Hydro 2000MU (A)
Analysis model: General purpose
Sensitivity: Enhanced
Particle RI: 1.570
Absorption: 0.1
Size range: 0.020 to 2000.000 um
Obscuration: 13.31 %
Dispersant Name: Propan-2-ol
Dispersant RI: 1.390
Weighted Residual: 0.806 %
Result Emulation: Off

Concentration: 0.0113 %Vol
Span : 5.122
Uniformity: 1.7
Result units: Volume
Specific Surface Area: 1.19 m^2/g
Surface Weighted Mean D[3,2]: 5.054 um
Vol. Weighted Mean D[4,3]: 43.889 um

d(0.1): 1.822 um   d(0.5): 22.034 um   d(0.9): 114.677 um

Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %
0.010		4.000		15.600		62.500		250.000		2000.000	
	11.07		13.05		9.62		18.74		0.79		
2.000		7.800		31.000		125.000		500.000			
	10.72		10.78		17.79		7.42		0.00		
4.000		15.600		62.500		250.000		2000.000			

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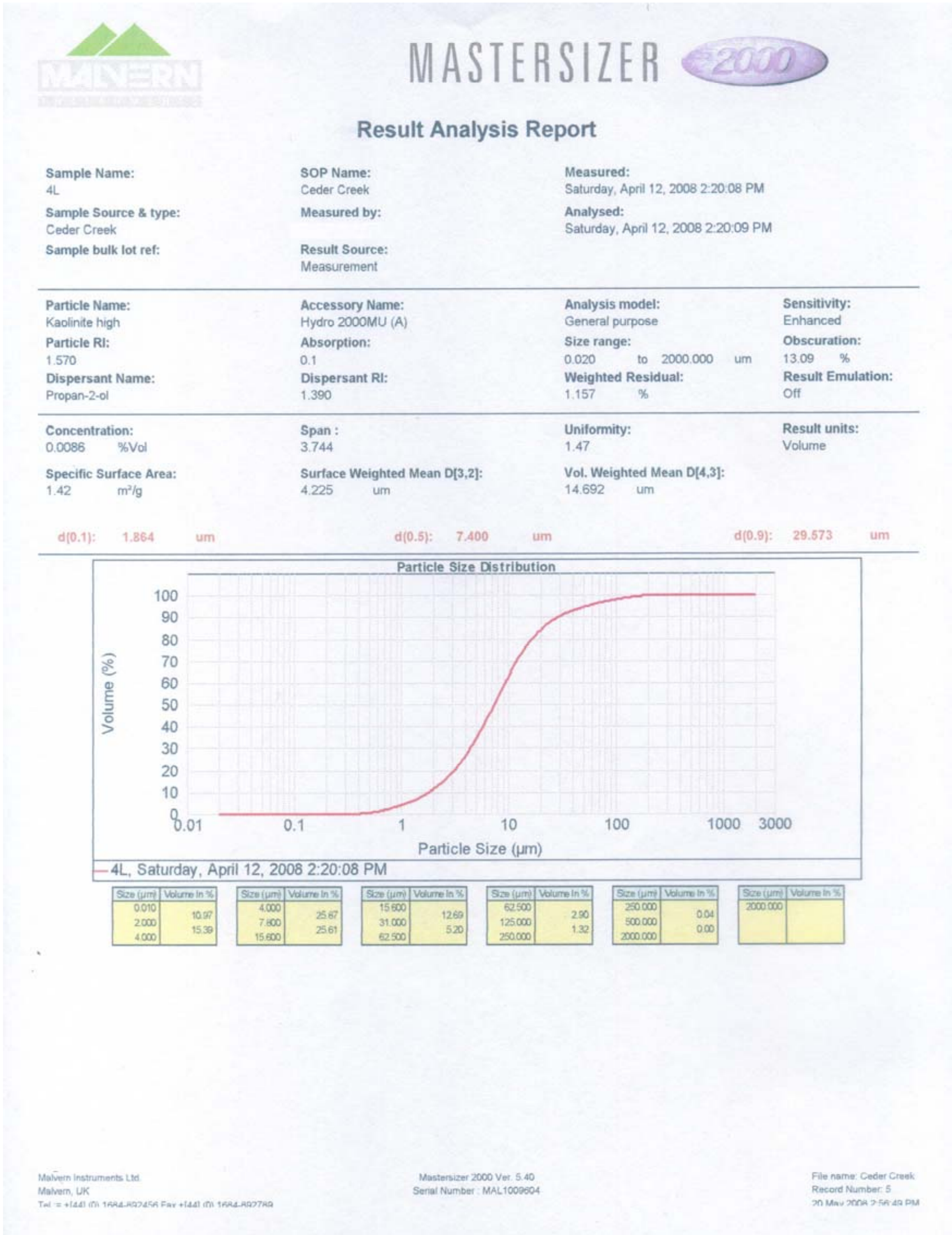
File name: Ceder Creek
Record Number: 15
20 May 2008 3:41:19 PM

Figure D.4. Grain size analysis of the upper bank at site 3.



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Result Analysis Report

Sample Name: 4L
Sample Source & type: Ceder Creek
Sample bulk lot ref:

SOP Name: Ceder Creek
Measured by:
Result Source: Measurement

Measured: Saturday, April 12, 2008 2:20:08 PM
Analysed: Saturday, April 12, 2008 2:20:09 PM

Particle Name: Kaolinite high
Particle RI: 1.570
Dispersant Name: Propan-2-ol

Accessory Name: Hydro 2000MU (A)
Absorption: 0.1
Dispersant RI: 1.390

Analysis model: General purpose
Size range: 0.020 to 2000.000 um
Weighted Residual: 1.157 %

Sensitivity: Enhanced
Obscuration: 13.09 %
Result Emulation: Off

Concentration: 0.0086 %Vol
Specific Surface Area: 1.42 m^2/g

Span : 3.744
Surface Weighted Mean D[3,2]: 4.225 um

Uniformity: 1.47
Vol. Weighted Mean D[4,3]: 14.692 um

Result units: Volume

d(0.1): 1.864 um   d(0.5): 7.400 um   d(0.9): 29.573 um

Size (μm)	Volume In %
0.010	
	10.97
2.000	
	15.39
4.000	

Size (μm)	Volume In %
4.000	
	25.67
7.800	
	25.61
15.600	

Size (μm)	Volume In %
15.600	
	12.69
31.000	
	5.20
62.500	

Size (μm)	Volume In %
62.500	
	2.90
125.000	
	1.32
250.000	

Size (μm)	Volume In %
250.000	
	0.04
500.000	
	0.00
2000.000	

Size (μm)	Volume In %
2000.000	

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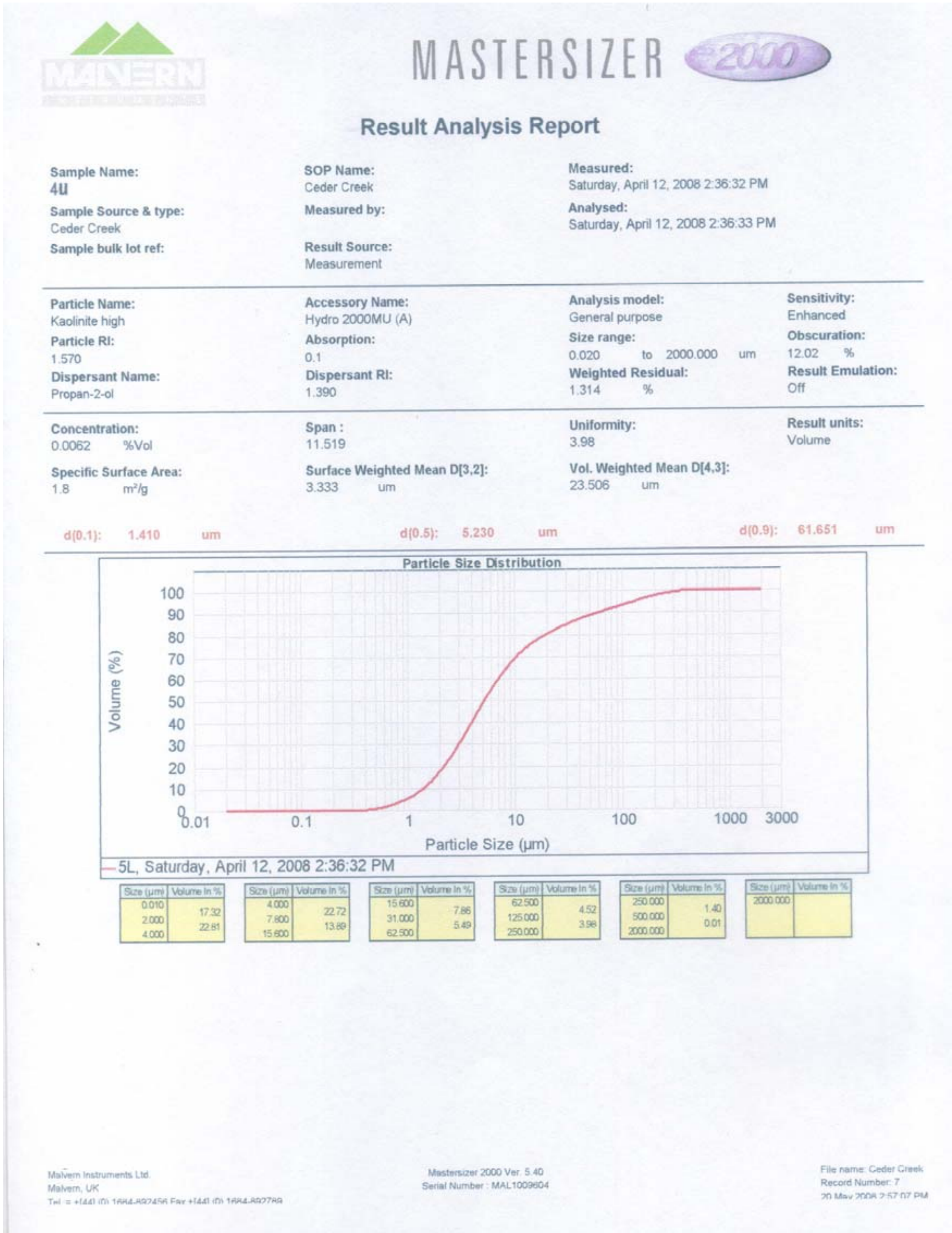
Serial Number : MAL1009604

File name: Ceder Creek
Record Number: 5
20 May 2008 2:56:49 PM

Figure D.5. Grain size analysis of the lower bank at site 4.



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Result Analysis Report

Sample Name: 4u
Sample Source & type: Ceder Creek
Sample bulk lot ref:
SOP Name: Ceder Creek
Measured by:
Result Source: Measurement
Measured: Saturday, April 12, 2008 2:36:32 PM
Analysed: Saturday, April 12, 2008 2:36:33 PM

Particle Name: Kaolinite high
Particle RI: 1.570
Dispersant Name: Propan-2-ol
Accessory Name: Hydro 2000MU (A)
Absorption: 0.1
Dispersant RI: 1.390
Analysis model: General purpose
Size range: 0.020 to 2000.000 um
Weighted Residual: 1.314 %
Sensitivity: Enhanced
Obscuration: 12.02 %
Result Emulation: Off

Concentration: 0.0062 %Vol
Specific Surface Area: 1.8 m^2/g
Span : 11.519
Surface Weighted Mean D[3,2]: 3.333 um
Uniformity: 3.98
Vol. Weighted Mean D[4,3]: 23.506 um
Result units: Volume

d(0.1): 1.410 um d(0.5): 5.230 um d(0.9): 61.651 um

Size (μm)	Volume In %
0.010	
	17.32
2.000	
	22.81
4.000	

Size (μm)	Volume In %
4.000	
	22.72
7.800	
	13.89
15.600	

Size (μm)	Volume In %
15.600	
	7.86
31.000	
	5.49
62.500	

Size (μm)	Volume In %
62.500	
	4.52
125.000	
	3.98
250.000	

Size (μm)	Volume In %
250.000	
	1.40
500.000	
	0.01
2000.000	

Size (μm)	Volume In %
2000.000	

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File name: Ceder Creek
Record Number: 7
20 May 2008 2:57:07 PM

Figure D.6. Grain size analysis of the upper bank at site 4.

MASTERSIZER 2000

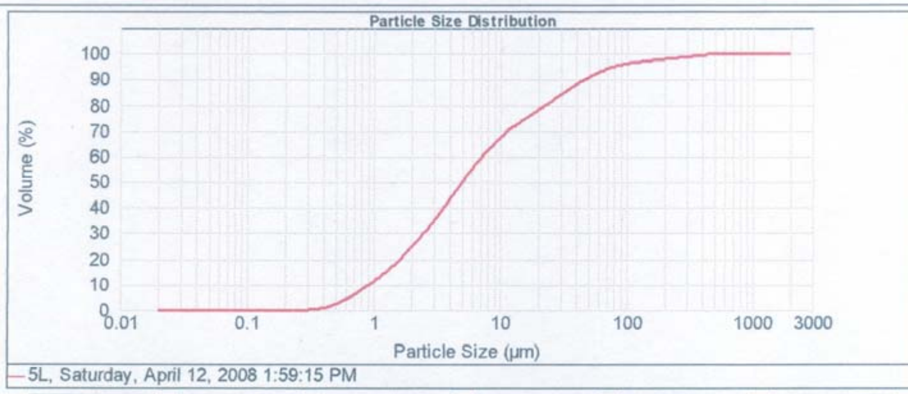
Result Analysis Report

Sample Name: 5L	**SOP Name:** Ceder Creek	**Measured:** Saturday, April 12, 2008 1:59:15 PM
Sample Source & type: Ceder Creek	**Measured by:**	**Analysed:** Saturday, April 12, 2008 1:59:16 PM
Sample bulk lot ref:	**Result Source:** Measurement	

Particle Name: Kaolinite high	**Accessory Name:** Hydro 2000MU (A)	**Analysis model:** General purpose	**Sensitivity:** Enhanced
Particle RI: 1.570	**Absorption:** 0.1	**Size range:** 0.020 to 2000.000 um	**Obscuration:** 27.00 %
Dispersant Name: Propan-2-ol	**Dispersant RI:** 1.390	**Weighted Residual:** 1.264 %	**Result Emulation:** Off

Concentration: 0.0134 %Vol	**Span :** 9.067	**Uniformity:** 3.83	**Result units:** Volume
Specific Surface Area: 2.36 m^2/g	**Surface Weighted Mean D[3,2]:** 2.538 um	**Vol. Weighted Mean D[4,3]:** 21.448 um	

d(0.1): 0.922 um   d(0.5): 5.008 um   d(0.9): 46.325 um



Size (μm)	Volume In %
0.010	
	24.44
2.000	
	18.78
4.000	

Size (μm)	Volume In %
4.000	
	18.83
7.600	
	12.39
15.600	

Size (μm)	Volume In %
15.600	
	9.90
31.000	
	8.87
62.500	

Size (μm)	Volume In %
62.500	
	3.52
125.000	
	1.69
250.000	

Size (μm)	Volume In %
250.000	
	1.32
500.000	
	0.27
2000.000	

Size (μm)	Volume In %
2000.000	

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Serial Number : MAL1009604

File name: Ceder Creek
Record Number: 3
20 May 2008 2:56:43 PM

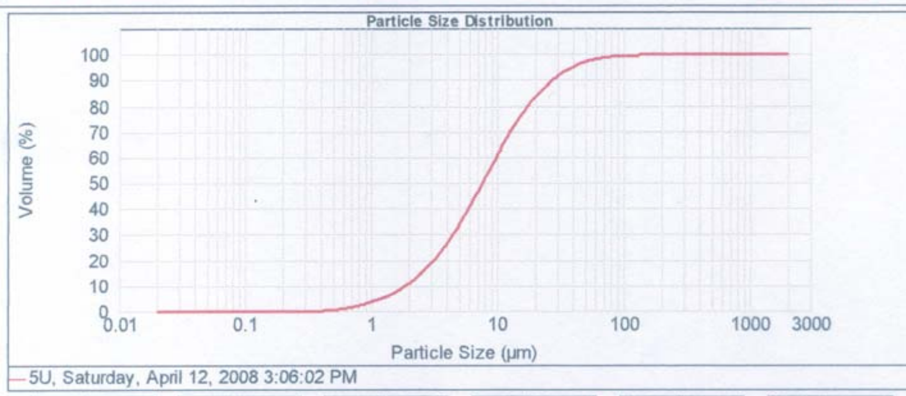
Figure D.7. Grain size analysis of the lower bank at site 5.

MASTERSIZER 2000

Result Analysis Report

Sample Name: 5U	**SOP Name:** Ceder Creek	**Measured:** Saturday, April 12, 2008 3:06:02 PM	
Sample Source & type: Ceder Creek	**Measured by:**	**Analysed:** Saturday, April 12, 2008 3:06:03 PM	
Sample bulk lot ref:	**Result Source:** Measurement		
Particle Name: Kaolinite high	**Accessory Name:** Hydro 2000MU (A)	**Analysis model:** General purpose	**Sensitivity:** Enhanced
Particle RI: 1.570	**Absorption:** 0.1	**Size range:** 0.020 to 2000.000 um	**Obscuration:** 16.63 %
Dispersant Name: Propan-2-ol	**Dispersant RI:** 1.390	**Weighted Residual:** 1.086 %	**Result Emulation:** Off
Concentration: 0.0114 %Vol	**Span :** 3.380	**Uniformity:** 1.17	**Result units:** Volume
Specific Surface Area: 1.38 m^2/g	**Surface Weighted Mean D[3,2]:** 4.347 um	**Vol. Weighted Mean D[4,3]:** 12.813 um	

d(0.1): 1.929 um   d(0.5): 7.635 um   d(0.9): 27.737 um



Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %
0.010		4.000		15.600		62.500		250.000		2000.000	
	10.54		24.53		15.59		1.26		0.04		
2.000		7.800		31.000		125.000		500.000			
	15.78		25.38		6.43		0.44		0.00		
4.000		15.600		62.500		250.000		2000.000			

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Serial Number : MAL1009604

File name: Ceder Creek
Record Number: 10
20 May 2008 2:57:24 PM

Figure D.8. Grain size analysis of the upper bank at site 5.

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MASTERSIZER 2000

Result Analysis Report

Sample Name: 7L
Sample Source & type: Ceder Creek
Sample bulk lot ref:

SOP Name: Ceder Creek
Measured by:
Result Source: Measurement

Measured: Saturday, April 12, 2008 2:44:35 PM
Analysed: Saturday, April 12, 2008 2:44:36 PM

Particle Name: Kaolinite high
Particle RI: 1.570
Dispersant Name: Propan-2-ol

Accessory Name: Hydro 2000MU (A)
Absorption: 0.1
Dispersant RI: 1.390

Analysis model: General purpose
Size range: 0.020 to 2000.000 um
Weighted Residual: 1.357 %

Sensitivity: Enhanced
Obscuration: 11.78 %
Result Emulation: Off

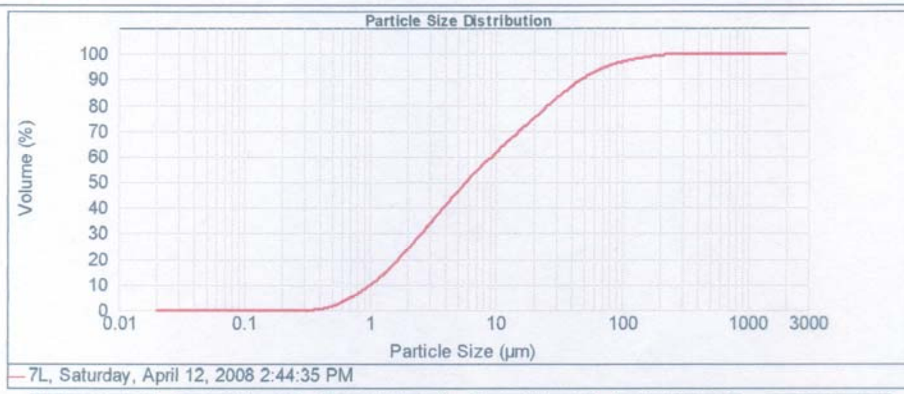
Concentration: 0.0057 %Vol
Specific Surface Area: 2.14 m^2/g

Span : 7.963
Surface Weighted Mean D[3,2]: 2.807 um

Uniformity: 2.72
Vol. Weighted Mean D[4,3]: 18.362 um

Result units: Volume

d(0.1): 1.021 um   d(0.5): 5.853 um   d(0.9): 47.623 um



Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %
0.010		4.000		15.600		62.500		250.000		2000.000	
	23.44		15.53		13.08		4.60		0.21		
2.000		7.800		31.000		125.000		500.000			
	17.35		13.58		10.28		1.92		0.00		
4.000		15.600		62.500		250.000		2000.000			

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File name: Ceder Creek
Record Number: 8
20 May 2008 2:57:13 PM

Figure D.9. Grain size analysis of the lower bank at site 7.

MASTERSIZER 2000

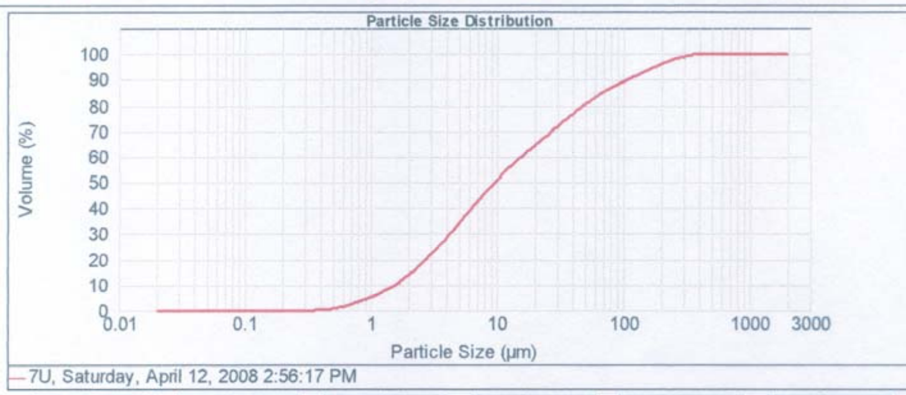
Result Analysis Report

Sample Name: 7U	**SOP Name:** Ceder Creek	**Measured:** Saturday, April 12, 2008 2:56:17 PM
Sample Source & type: Ceder Creek	**Measured by:**	**Analysed:** Saturday, April 12, 2008 2:56:18 PM
Sample bulk lot ref:	**Result Source:** Measurement	

Particle Name: Kaolinite high	**Accessory Name:** Hydro 2000MU (A)	**Analysis model:** General purpose	**Sensitivity:** Enhanced
Particle RI: 1.570	**Absorption:** 0.1	**Size range:** 0.020 to 2000.000 um	**Obscuration:** 11.50 %
Dispersant Name: Propan-2-ol	**Dispersant RI:** 1.390	**Weighted Residual:** 1.052 %	**Result Emulation:** Off

Concentration: 0.0077 %Vol	**Span :** 11.276	**Uniformity:** 3.34	**Result units:** Volume
Specific Surface Area: 1.45 m^2/g	**Surface Weighted Mean D[3,2]:** 4.134 um	**Vol. Weighted Mean D[4,3]:** 35.973 um	

d(0.1): 1.559 um d(0.5): 9.593 um d(0.9): 109.731 um



Size (μm)	Volume In %
0.010	
	13.71
2.000	
	14.73
4.000	
	16.83
7.800	
	14.44
15.600	
	12.57
31.000	
	11.47
62.500	
	7.56
125.000	
	6.55
250.000	
	2.14
500.000	
	0.00
2000.000	

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File name: Ceder Creek
Record Number: 9
20 May 2008 2:57:18 PM

Figure D.9. Grain size analysis of the upper bank at site 7.

MASTERSIZER 2000

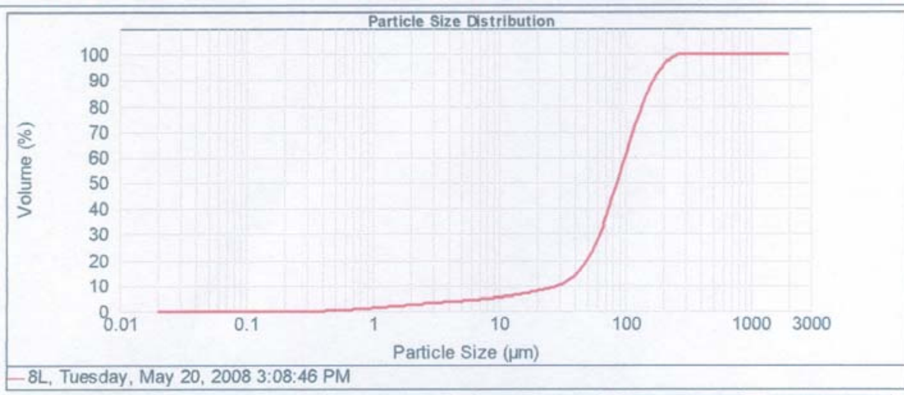
Result Analysis Report

Sample Name: 8L	**SOP Name:** Ceder Creek	**Measured:** Tuesday, May 20, 2008 3:08:46 PM
Sample Source & type: Ceder Creek	**Measured by:**	**Analysed:** Tuesday, May 20, 2008 3:08:47 PM
Sample bulk lot ref:	**Result Source:** Measurement	

Particle Name: Kaolinite high	**Accessory Name:** Hydro 2000MU (A)	**Analysis model:** General purpose	**Sensitivity:** Enhanced
Particle RI: 1.570	**Absorption:** 0.1	**Size range:** 0.020 to 2000.000 um	**Obscuration:** 12.52 %
Dispersant Name: Propan-2-ol	**Dispersant RI:** 1.390	**Weighted Residual:** 0.430 %	**Result Emulation:** Off

Concentration: 0.0465 %Vol	**Span :** 1.589	**Uniformity:** 0.487	**Result units:** Volume
Specific Surface Area: 0.278 m^2/g	**Surface Weighted Mean D[3,2]:** 21.578 um	**Vol. Weighted Mean D[4,3]:** 94.064 um	

d(0.1): 29.790 um   d(0.5): 87.075 um   d(0.9): 168.109 um



Size (µm)	Volume In %
0.010	2.34
2.000	1.13
4.000	

Size (µm)	Volume In %
4.000	1.17
7.800	2.06
15.600	

Size (µm)	Volume In %
15.600	3.68
31.000	19.38
62.500	

Size (µm)	Volume In %
62.500	44.62
125.000	24.68
250.000	

Size (µm)	Volume In %
250.000	0.74
500.000	0.00
2000.000	

Size (µm)	Volume In %
2000.000	

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Serial Number : MAL1009604

File name: Ceder Creek
Record Number: 12
20 May 2008 3:40:58 PM

Figure D.11. Grain size analysis of the lower bank at site 8.

MASTERSIZER 2000

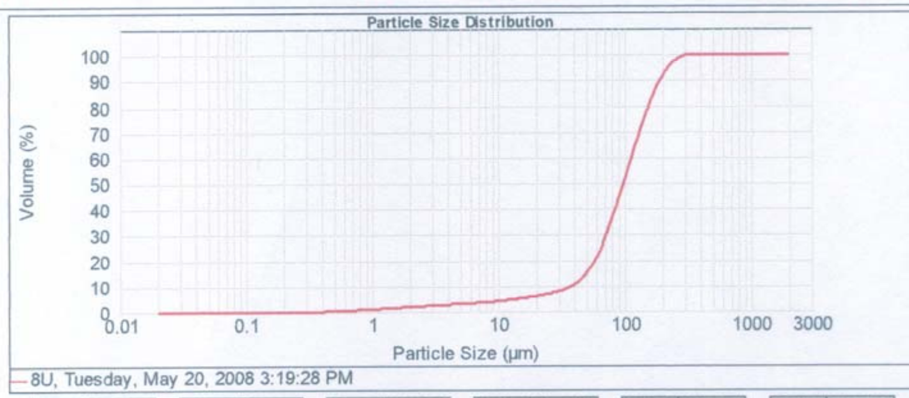
Result Analysis Report

Sample Name: 8U	**SOP Name:** Ceder Creek	**Measured:** Tuesday, May 20, 2008 3:19:28 PM
Sample Source & type: Ceder Creek	**Measured by:**	**Analysed:** Tuesday, May 20, 2008 3:19:29 PM
Sample bulk lot ref:	**Result Source:** Measurement	

Particle Name: Kaolinite high	**Accessory Name:** Hydro 2000MU (A)	**Analysis model:** General purpose	**Sensitivity:** Enhanced
Particle RI: 1.570	**Absorption:** 0.1	**Size range:** 0.020 to 2000.000 um	**Obscuration:** 13.96 %
Dispersant Name: Propan-2-ol	**Dispersant RI:** 1.390	**Weighted Residual:** 0.362 %	**Result Emulation:** Off

Concentration: 0.0640 %Vol	**Span :** 1.538	**Uniformity:** 0.478	**Result units:** Volume
Specific Surface Area: 0.226 m²/g	**Surface Weighted Mean D[3,2]:** 26.530 um	**Vol. Weighted Mean D[4,3]:** 107.232 um	

d(0.1): 38.024 um d(0.5): 98.814 um d(0.9): 190.004 um



Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %
0.010	1.62	4.000	0.85	15.600	2.84	62.500	43.33	250.000	2.33	2000.000	
2.000	0.88	7.800	1.63	31.000	15.13	125.000	31.18	500.000	0.00		
4.000		15.600		62.500		250.000		2000.000			

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File name: Ceder Creek
Record Number: 13
20 May 2008 3:41:07 PM

Figure D.12. Grain size analysis of the upper bank at site 8.

REFERENCES

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