CHARACTERIZING AND MAPPING SEDIMENT ERODIBILITY OF TUTTLE CREEK LAKE IN NORTHEAST KANSAS

by

PENNY M. BLOEDEL

B.S., United States Military Academy, 2000
M.S., Missouri University of Science and Technology, 2006

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College of Arts and Sciences

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Approved by:

Major Professor
Charles W. Martin

Abstract

Tuttle Creek Dam was built in 1962 after near-record flooding in the Kansas River watershed. It has been in operation for over 50 years. In that time, nearly half of its storage capacity has been filled by sediment, reducing its ability to serve its intended purpose under current operations. The Corps of Engineers authorized a study to examine the sediment in Tuttle Creek Lake and determine management strategies to extend its lifespan. This report examines the erodibility of the sediment as a function of depth and distance to dam. Eight sediment cores were tested and analyzed for two erodibility parameters, critical shear stress and erodibility coefficient. After directly comparing these parameters it was determined that Tuttle Creek Lake sediment ranges from erodible to very erodible regardless of depth or location. Analyzing for locational and depth patterns in erodibility coefficients indicated that both influence the erodibility of sediment, with depth being the stronger factor. These results indicate that locations further upstream from the dam and greater depths are the least erodible. Sedimentation patterns were mapped onto a three dimensional model in ArcMap. It is hoped that this research will assist Corps of Engineers leadership in deciding which management practices to pursue for Tuttle Creek Lake.

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Chapter 1 - Introduction and Purpose

In July 1951, after a five-day burst of rain during an already wet rainy season, people living near the Kansas River and its tributaries experienced the worst flood in 48 years. Although authors of the post-flood report concluded that the 1951 flood's frequency was once every few hundred years, it was at the time just the latest and costliest in a series of large flood events in the Kansas River basin (Report of Flood Protection, 1953). Repeated efforts to build flood control measures on the Kansas River and its tributaries resulted in scattered levees and only two reservoirs being built prior to the 1951 flood (USACE, 2015). After that flood Congress authorized the construction of multiple flood mitigation measures, including several large dams that have since impounded millions of acre-feet of water and, in addition to their stated purpose of providing flood control, provided considerable recreation and economic opportunities to the surrounding areas (KWO, 2010) (Figure 1). However, dams also come with consequences for the surrounding environment. One such consequence is the impoundment of sediment, which creates hydrologic and geomorphic impacts on the dams' river systems both above and below the dam. Additionally, as all of these post-flood dams came into operation in the 1960s and 1970s, they and their impoundments are now showing the physical effects of the collected sediments.

One large dam and reservoir that is of particular concern is Tuttle Creek Dam and Lake. One of the two largest bodies of water in Kansas, Tuttle Creek Lake also has one of the fastest sedimentation rates among large federal reservoirs in Kansas. (Because this reservoir is called a lake by USACE and other entities, the terms "reservoir" and "lake" are used interchangeably in this study). Tuttle Creek Lake was initially capable of storing 424,000 acre-feet of water in its conservation pool, but sedimentation had reduced this capacity by over 41% by 2015 (Juracek, 2015). In order to determine ways to mitigate the sedimentation, lake managers need to understand the characteristics of the sediment—its properties, composition, and location. In this report, I want to examine one particular characteristic of the sediment, erodibility, as part of the U.S. Army Corps of Engineers' greater lake management strategy for Tuttle Creek Lake in order to prolong the lake's usability. My specific objectives are to:

(1) Analyze the erodibility of sediment throughout Tuttle Creek Lake as a function of critical shear stress, distance from dam, and depth.

(2) Create a detailed sediment erodibility map of accumulated sediment of Tuttle Creek Lake. This map will portray the spatial distribution of general sediment erodibility throughout Tuttle Creek Lake.

It is my intent that this report will provide a detailed depiction of sediment erodibility in Tuttle Creek Lake. This will aid engineers and managers at the U.S. Army Corps of Engineers (USACE) as they assess the feasibility of available methods to manage and remove sedimentation in Tuttle Creek Lake, extending the lifespan and utility of the lake for both the surrounding communities and those downstream from it. Ultimately, when combined with additional studies of Tuttle Creek Lake, this report will contribute to the body of knowledge about how to manage the U.S.'s aging hydraulic infrastructure, particularly dams.

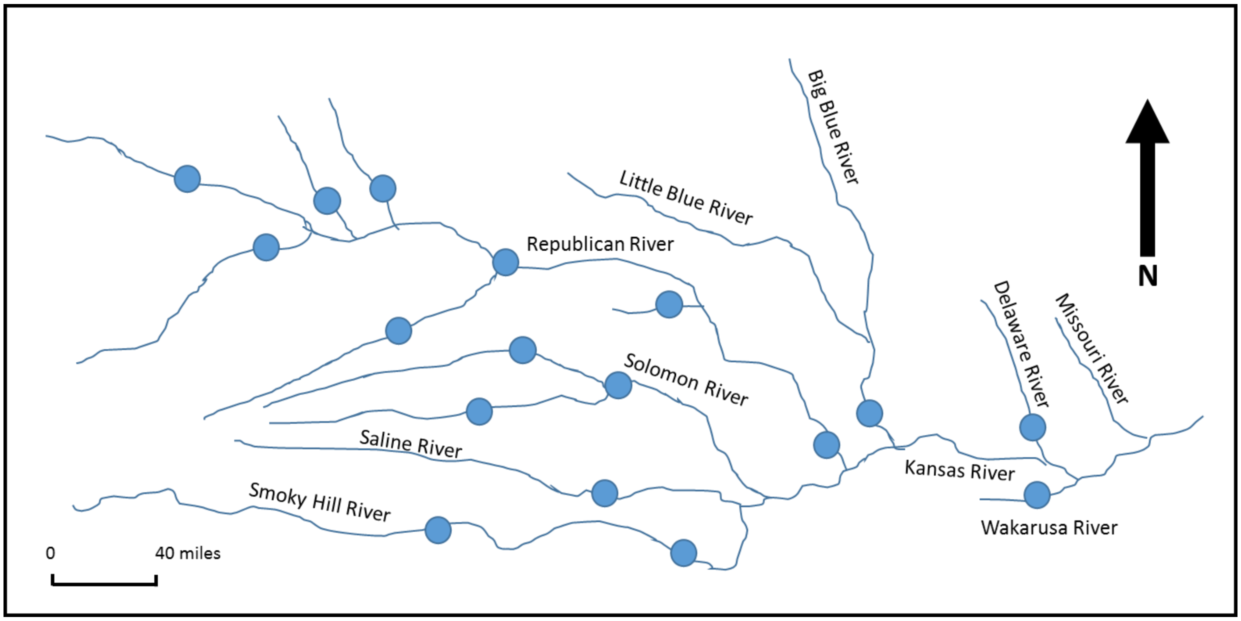

Figure 1. Federal reservoirs in northern Kansas and southern Nebraska (Adapted from USACE, 1984).

Chapter 2 - Literature Review

Erodibility Parameters

As sediment is deposited and takes up more space in Tuttle Creek Lake, it impacts economic and natural assets both at the lake and downstream of the dam. The deposited sediment's erodibility, or resistance to erosion, is one parameter that lake managers must understand when determining sediment management solutions. Assessment and determination of sediment (i.e. soil) erodibility is essential when planning, managing, and maintaining structures and adjacent terrain in and around reservoirs and other water features. Evaluating erosion resistance of deposited cohesive sediments such as those found in Tuttle Creek Lake can be difficult because of the interacting physical and elcetro-chemical properties in the sediment (Hanson and Simon, 2001; Mazurek, *et al.*, 2001; Juracek, 2002). Cohesive materials behave differently than do non-cohesive materials. Methods commonly used to analyze non-cohesive materials, such as particle size, are not always useful when analyzing cohesive sediments' erodibility; methods that measure electro-chemical characteristics, such as critical shear stress and the erodibility coefficient, provide more reliable results (Simon *et al.*, 2011).

Typically, cohesive soils erode in three ways: surface of the bed, mass erosion of the bed, and entrainment of fluid mud (Simon *et al.*, 2010). The common assumption when evaluating erodibility is that the rate of erosion is proportional to the excess shear stress, as expressed below (Hanson and Cook, 1997):

$$\varepsilon_r = k_d\ (\tau_e - \tau_c) \qquad (1)$$

where

k_d = the erodibility or detachment coefficient (cubic centimeters per Newton-second)
τ_e = the effective hydraulic shear stress (Pascals)
τ_c = the critical shear stress (Pascals)

As illustrated, the effective shear stress must be greater than the critical shear stress in order for erosion to begin; k_d and τ_c are considered excess stress parameters in that erosion rate is determined by these parameters and the relationship between τ_e and τ_c (Hanson and Simon, 2001). Increases in k_d will increase the erosion rate while increases in τ_c will decrease the erosion rate.

Numerous examples of this equation are established in the literature (Foster, 1977; Dillaha and Beasley, 1983; Temple, 1985; Stein and Nett, 1997; Hanson and Cook, 2004; Al-Madhhachi *et al.*, 2013). Comparisons with other soil characteristics indicate that the complexity of soils demands the "testing of specific soils and conditions to determine erodibility" (Hanson and Cook, 2004). In other words, no universal relationship between these parameters and other soil characteristics has been found in the literature.

In their 2001 study, Hanson and Simon (2001) also concluded that while k_d data spanned six orders of magnitude and τ_c spanned four orders of magnitude, these parameters appeared to have an inverse relationship expressed as

$$k_d = 0.2\ \tau_c^{-0.5} \qquad (2)$$

Simon *et al.*, (2011) updated this equation based on further JET streambank analysis to

$$k_d = 1.62\tau_c^{-0.838} \qquad (3)$$

Karmaker and Dutta (2010) also found an inverse relationship between the erodibility coefficient and the critical shear stress, furthering the suggestion that soils with low k_d have a high τ_c and vice versa.

Testing for erodibility in soils is done by several methods, with the submerged impinging water jet being a commonly used method in the laboratory (Hanson, 1991; Mazurek *et al.*, 2001; Karmaker and Dutta, 2010; Cossette *et al.*, 2012). Initially, Hanson (1991) developed a soil-dependent jet index that depicted an empirical relationship between erosion and the jet index (Hanson and Simon, 2001). However, this index approach was superseded by Hanson and Cook's (1997) development of erodibility parameters based on research done by Stein *et al.* (1993) and validated by Stein and Nett (1997). Stein and Nett (1997) determined that when jet of water at height J_i above a soil bed is discharged with a constant velocity, at distance J_p the velocity of the jet will diffuse radially from the centerline, with the centerline being the velocity maximum. The jet penetrates the soil causing scour and creating a scour bed, eventually reaching a maximum depth. This happens because with an increasing scour bed, energy dissipation also increases. With less energy from the jet, applied shear stress decreases. The distance between the jet nozzle and the maximum scour is the equilibrium depth, J_e (Stein and Nett, 1997) (Figure 2). Put differently, when hydraulic shear equals the critical shear stress, the scour depth is known as the equilibrium depth. The critical shear stress is then determined by the following equation:

$$\tau_c = \tau_0 * (J_p/J_e)^2 \quad (4)$$

where

τ_0 = the maximum applied bed shear stress within the potential core
J_p = potential core length from the jet's origin
J_e = distance to equilibrium depth of scour from the jet nozzle (Stein and Nett, 1997).

Observing that the time to reach equilibrium depth could take weeks or months, Blaisdell *et al.*, (1981) developed a function to forecast equilibrium scour if the time to achieve it is unreasonably long, assuming a logarithmic-hyperbolic relationship between scour and time. From this, Hanson and Cook (1997) developed a logarithmic-hyperbolic method to determine τ_c, with k_d estimated from "curve-fitting measured values of scour depth versus time and minimizing the error of the measured time versus the predicted time" (Simon *et al.*, 2010). This method has become a common way to evaluation erodibility, although additional research

(Simon *et al.*, 2010: Daly *et al.*, 2013) has indicated that Blaisdell *et al.*'s solution tends to under-predict erosion while not always reaching a reasonable solution. As a response to the faults in the Blaisdell *et al.* solution, Rob Thomas of the Agricultural Research Service and the USDA's National Sedimentation Laboratory developed an iterative solution process based on Hanson and Cook (1997) and tested by Simon *et al.* (2010) and Cossette *et al.* (2012). These studies found that Thomas's method over-predicted critical shear stress and erodibility values.

Reservoir Sedimentation

When engineers plan for the lifespan of a dam, they must consider several factors: how long the dam is needed to perform its intended function, materials used for its construction, and the rate of sedimentation into the resultant reservoir (Gebrigiorgis *et al.*, 2012). A dam can fail in two ways: through its structure or through its performance. Sedimentation can cause a performance failure in several ways. For dams whose purpose is flood control or water storage, sediment displaces water in the reservoir, diminishing the ability to hold water during flood events or simply to provide necessary amounts of water for the public (Fan and Morris, 1992). Sediment can also damage hydropower equipment or raise the channel or reservoir bed enough to prevent or curtail navigation (Fan and Morris, 1992).

Anthropogenic lakes are shaped by the river valleys they occupy and are commonly long and narrow, with shallower upstream areas and deeper downstream areas near their dams. This causes different sediment distribution patterns than those found in natural lakes (Shotbolt *et al.*, 2005). According to Morris and Fan (1998), reservoir sedimentation occurs in one of four ways: delta, wedge, tapering, and uniform (Figure 3). Generally, in long, narrow reservoirs that are not subject to drawdowns, such as Tuttle Creek Lake, sediment will be deposited in a tapering or delta profile. Tapering deposits tend to occur in longer reservoirs where a constant pool of water allows the sediment to continue towards the dam, gradually sorting sediment as the water approaches the dam (Morris and Fan, 1997). Sediment particle size and deposition thickness decrease as water approaches the dam (Morris and Fan, 1998). A delta deposit acts and looks much like a river delta. In this case, coarser sediment drops out of suspension as a river flows into a reservoir, creating a topset bed with coarse and fine materials (Fan and Morris, 1992). A delta's foreset deposits occur where the delta is actively moving or advancing; there is generally a marked change in both slope and particle size from the topset, sometimes accompanied by a change in the water's flow depending on the amount of sediment remaining in suspension (Fan and Morris, 1992). Tributaries can alter this pattern by adding unsorted suspended sediment downstream of a reservoir delta, potentially allowing coarser materials to enter into intakes or turbines. Tributaries can deposit their sediment in a way that disconnects the tributary from the main channel, reducing storage capacity (Fan and Morris, 1992). Additionally, the generally large shoreline to surface area of reservoirs cause more unsorted sediment to enter the system directly through erosion or bank failure or cause sediment to move more quickly through a system with less sorting (Shotbolt, 2005). These sources of unsorted sediment can degrade a lake's performance.

Finally, nearly all dams act as a barrier to sediment flow, disconnecting upstream parts of a river system from its downstream sections. The ratio of the amount of sediment blocked by the dam to the amount entering the reservoir is called the trapping efficiency. Gunnar Brune (1953) developed a method for estimating the trapping efficiency of reservoirs as a function. Studying 44 reservoirs across the United States, Brune determined that there is a relationship between the storage capacity to sediment inflow ratio and a reservoir's trapping efficiency: as the storage capacity to inflow ratio gets smaller, the trapping efficiency will also decrease (Brune, 1953)

(Figure 4). This is due to the smaller amount of available volume behind the dam; more water (and therefore sediment) must flow through or over a dam. Although this method has some limitations—its utility lies in long-term efficiency estimates and Brune himself acknowledged that trap efficiency can also depend on basin shape or sediment type—Brune's method is widely used in reservoir research and design (Morris and Fan, 1998).

Previous studies of Tuttle Creek Lake

Government reports account for most of the published sediment and water quality literature on Tuttle Creek Lake. The earliest published study, in 1971, less than ten years after closure of the dam, indicated that the percentages of clay, silt, and sand did not vary much in the lake and that there was general uniformity in particle size (Schwartz and Marzolf, 1971). Further sediment studies were not published until 30 years later and after the largest flood event since the construction of Tuttle Creek Dam. One 2002 study on nutrients and chemicals in the sediment confirmed Schwartz and Marzolf's earlier finding of uniformity in the sediment deposition (Juracek and Mau, 2002). This same study also found that the lake had filled approximately 33% of the planned water-storage capacity, a greater change from the earlier study where some places had experienced no sedimentation as a result of impoundment (Juracek and Mau, 2002; Schwartz and Marzolf, 1971). Though the findings on nutrients and chemicals are outside the scope of this project, the 2002 study is important because the authors conducted a bathymetric survey in 1999, which included cross-section profiles throughout the lake (Juracek and Mau, 2002). Their survey provided information on bottom thickness of the sediment as determined through comparison of a 1962 survey done around the time of closure and the 1999 survey, both in- and out-of-channel (Juracek and Mau, 2002) (Figures 5 and 6).

Finally, Tuttle Creek Lake is a high sediment trapping lake, as defined by Brune. Nearly 50 years after coming into operation, Tuttle Creek Lake had a sediment trapping efficiency of 98%, with most of its sediment coming from sources other than the channel bed (Juracek, 2011) .

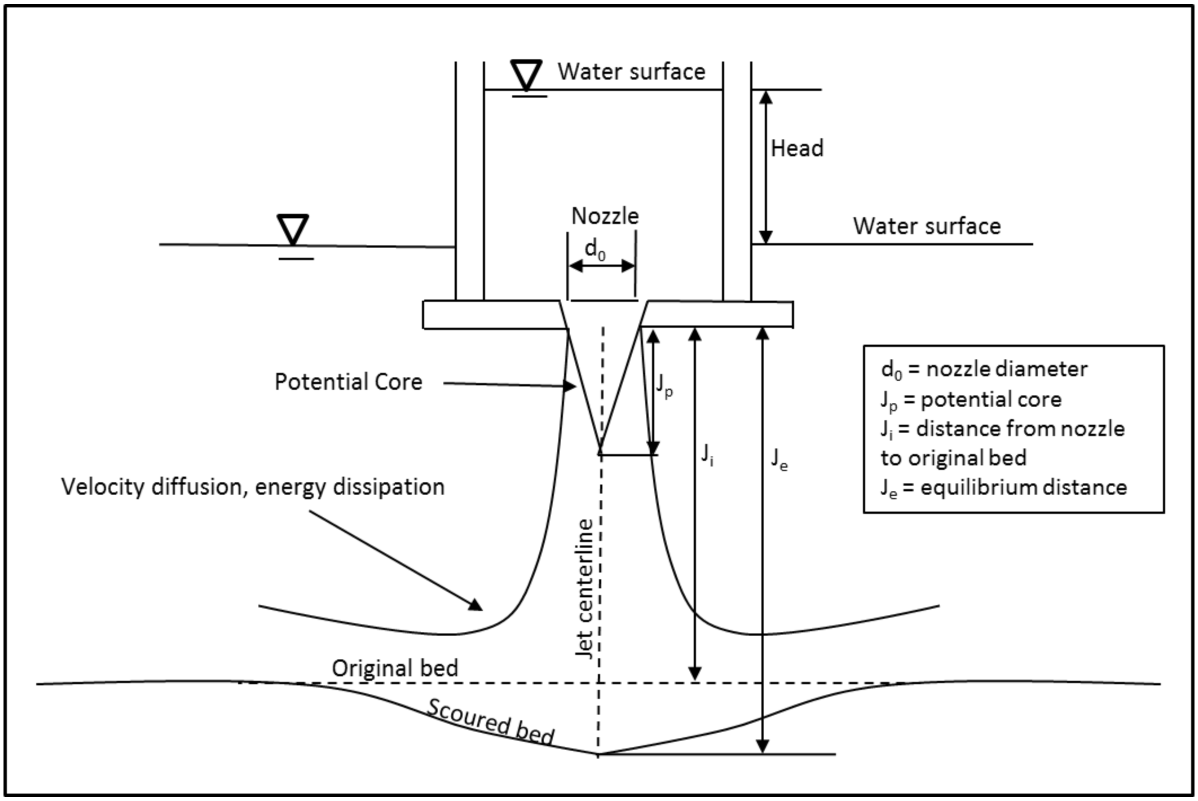

Figure 2. Sketch of jet scour diffusion (Adapted from Hanson and Simon, 2001).

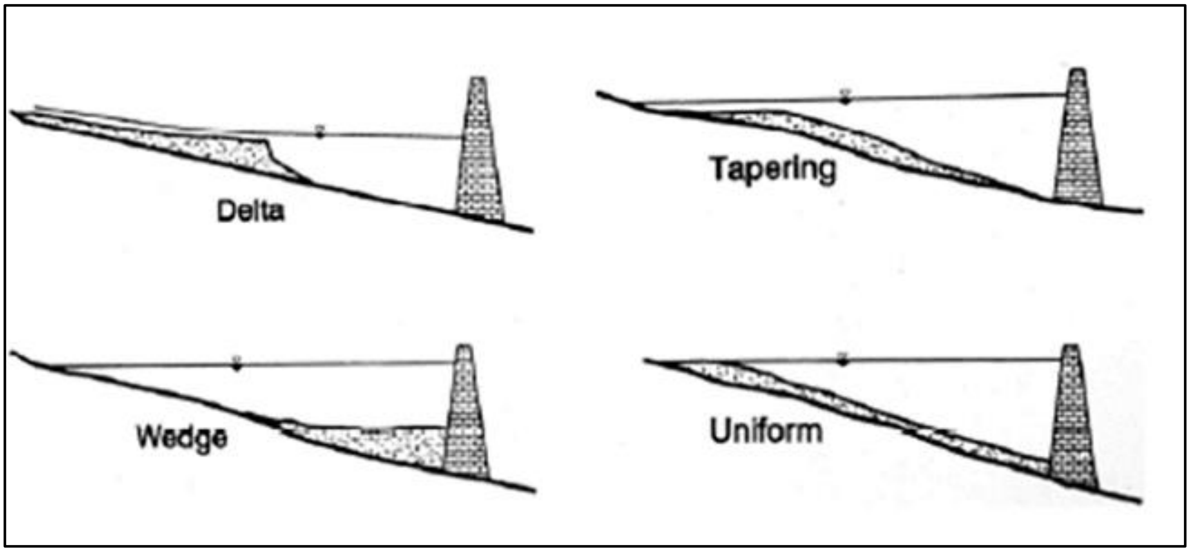

Figure 3. Generalized diagram of reservoir sediment profiles (Morris and Fan, 1998).

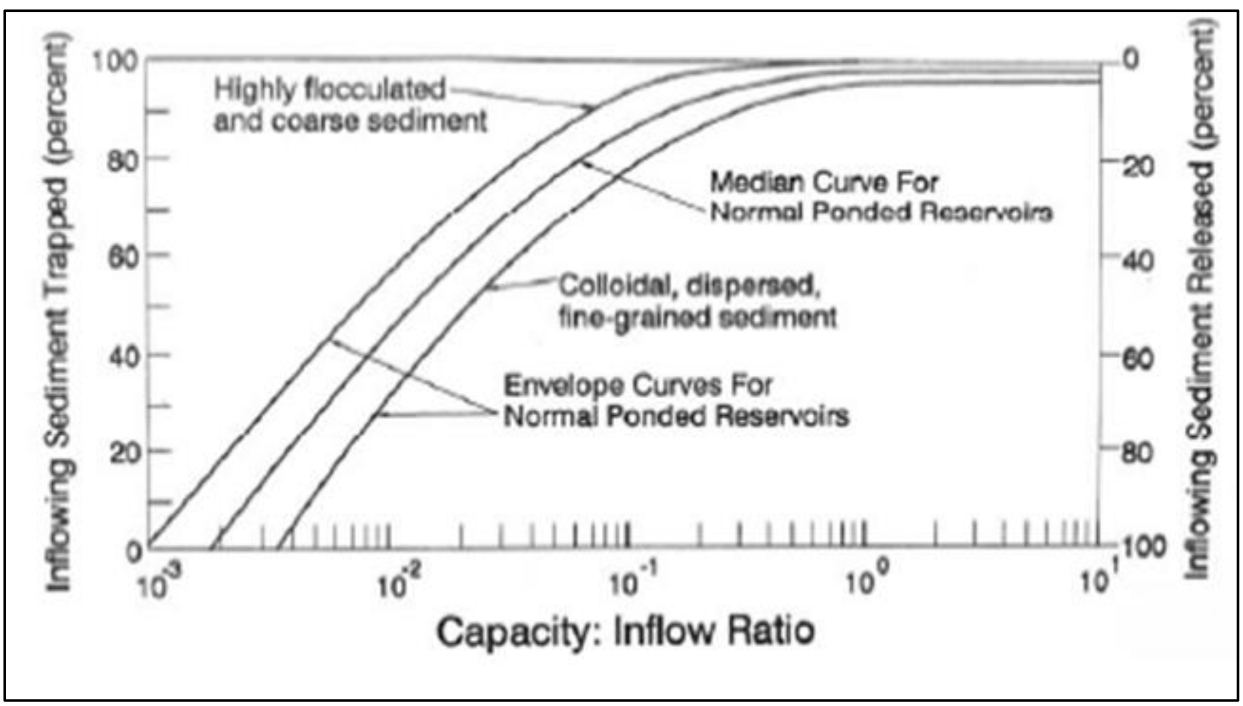

Figure 4. Brune curve for trapping efficiency estimation (Morris and Fan, 1998, adapted from Brune 1953).

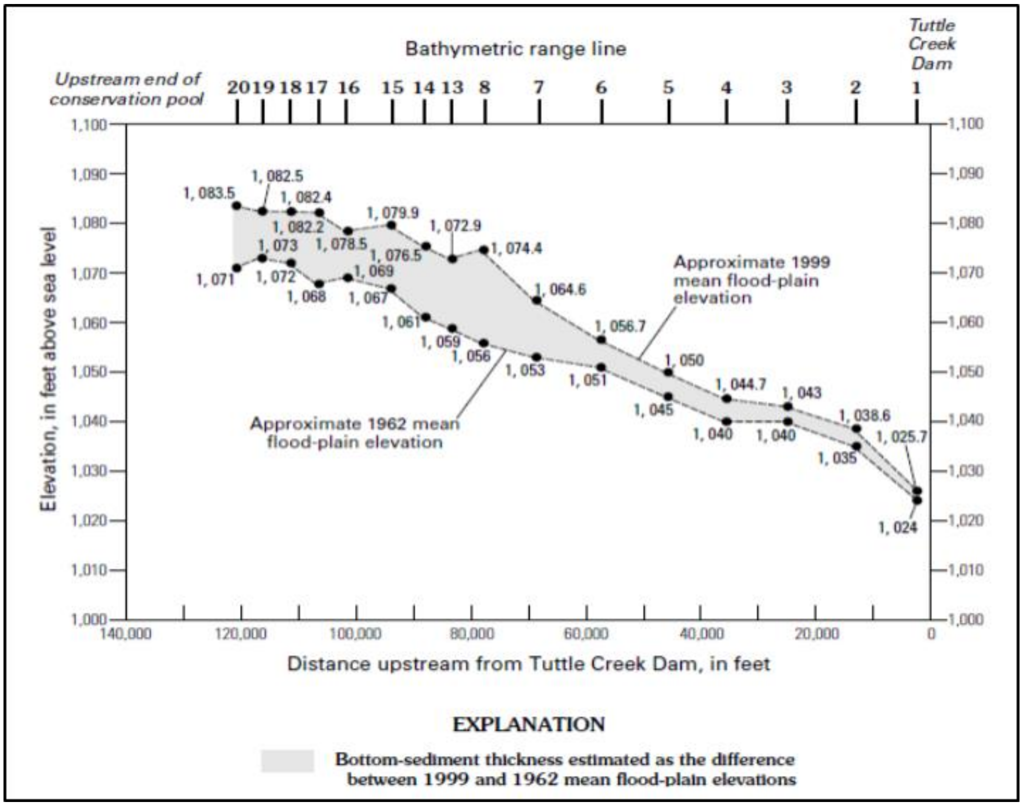

Figure 5. Out-of-channel (floodplain) bottom-sediment thickness (Juracek and Mau, 2002).

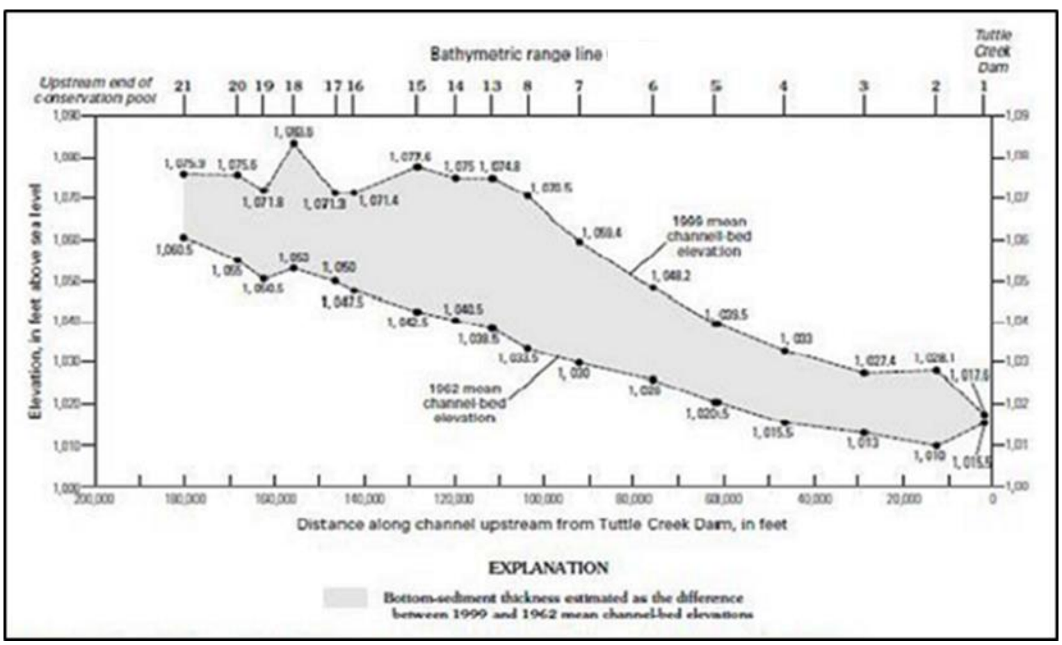

Figure 6. In-channel bottom-sediment thickness (Juracek and Mau, 2002).

Chapter 3 - Study Area

The study area for this report is Tuttle Creek Lake, from the confluence of Fancy Creek and the Big Blue River, roughly the area where Highway 16 crosses the lake, to the dam (Figure 7). This area of the lake is important because it represents an area of active sedimentation in the conservation pool; upstream of the Highway 16 bridge, the lake is no longer inundated except during flood events. Only the stream channels carry water. Because Tuttle Creek Lake's watershed is virtually identical to the Big Blue River's watershed (only the final five miles of the Big Blue River lie below Tuttle Creek Dam) is described in terms of watershed, climate, land use, and the lake itself.

The Tuttle Creek Lake watershed is approximately 9600 square miles and lies in Nebraska and Kansas, with approximately 75% lying in Nebraska (Figure 8). Like other basins in Kansas and Nebraska, the watershed encompasses several physiographic regions, although in general it is made up of alternating shale and limestone layers with some local sandstone layers (USACE, 1968). The upper basin comprises the High Plains and Plains Border Sections. The High Plains Section originated as fluvial and windblown deposits of both consolidated and unconsolidated silt with smaller amounts of sand and gravel, up to 200 feet thick. It is flat with little topographic relief (Fenneman, 1931 and USACE, 1968). The Plains Border Section marks the more active erosional area of the Great Plains Province. Here the sandstone sits atop weaker shale layers. It is marked by pronounced hills, outcrops, and escarpments of up to 300 feet (Fenneman, 1931). The lower portion of the basin is made up of the Dissected Till Section of the Central Lowland Province. This section is the result of Pleistocene glacial activity and contains deposits ranging from clay-sized particles to boulders. It is generally covered in a layer of glacial and windblown loess that ranges from a few feet to several dozen feet in places; there is little exposed bedrock in this section. Although heavily dissected, as the name suggests, there is little relief in this section (Fenneman, 1938). The Osage Section marks the lowermost part of the watershed, including the lake itself, and is known locally as the Flint Hills. These hills are primarily chert-bearing limestones in the Tuttle Creek Lake area with thin, rocky soils (Fenneman, 1938). Several tributaries drain into the Big Blue River upstream of Tuttle Creek Lake, including the Little Blue River, Black Vermillion River, and Mill Creek. Although there are over 100 small off-stream impoundments within the watershed, Tuttle Creek Lake is the only impoundment on any major stream (KWO, 2010).

Climate in the basin changes in general from northwest to southeast, following the general decrease in elevation in the same direction. Climate data from the thirty-year period ending in 2010 indicate annual precipitation lows in the upper basin of 24”-26” increasing to 32”-36” in the lower basin (PRISM, 2015). Precipitation ranges from snowfall in the winter to high-intensity thunderstorms in the spring and summer, with most of the precipitation falling in the warmer months (USACE, 1968). Mean, minimum, and maximum temperatures also increase from north to south; normalized temperature data for the thirty year period 1981-2010 show a mean temperature low of 50-54° F in the upper basin to 54-57° F in the lower basin (PRISM, 2015). Temperatures range from highs that exceed 100° F in the summer to below 0° F in winter.

Land use in the watershed is predominantly agricultural, with smaller amounts of wooded and populated areas (Figure 9). In the 2012 Agricultural Census (USDA, 2014), croplands, pasture, and woodlands comprised 68.8%, 15.3%, and 1.2%, respectively, of the total land use, with some Nebraska counties planting over 90% of their land in crops. In Kansas, croplands account for less of the total land usage, with pastures covering over 20% of the land in Marshall and Washington Counties (USDA, 2014). Corn and soybeans are the primary crops in the watershed with lesser amounts of wheat and hay harvested (USDA, 2014). The watershed is overwhelmingly rural: only two areas with population greater than 21,000 lie in the watershed upstream of Tuttle Creek Lake (Juracek and Mau, 2002).

Tuttle Creek Lake lies approximately six miles north of Manhattan, Kansas, in Riley, Pottawatomie, and Marshall Counties. It is an impoundment of the Big Blue River. Tuttle Creek Lake is a USACE-maintained reservoir built primarily as a flood-control agent. Secondary purposes include ensuring navigation on the Missouri River and recreational activities. Currently, the conservation pool extends from the dam to Highway 16 Bridge, a straight-line distance of about 12 miles. North of the Highway 16 Bridge, the lake is exclusively flood storage. The lake elevation is maintained at or near 1075' above MSL, although weather extremes affect the amount of water stored in the reservoir. Operating since 1962, Tuttle Creek Lake was designed at total storage of 2,367,000 acre-feet, with 228,000 acre-feet allocated for sediment storage, 197,000 acre-feet for conservation storage, and 1,942,000 acre-feet for flood storage (USACE, 1988). The sediment is currently within its designated allocation; once this amount is exceeded, sediment storage affects the conservation pool allocation (John Shelley, USACE, Oral Communication, 2015). The sediment itself is uniform and does harbor some agricultural contaminants that do not alter the quality of the sediment (Schwartz and Marzolf, 1971 and Juracek and Mau, 2002).

The Dissected Till Plains and Osage Plains comprise the immediate area around Tuttle Creek Lake. The surrounding bedrock and soils are characteristic of these two sections, with glacial till prevalent north of the Highway 16 Bridge and alternating shales and chert to the south. At higher elevations, soils are rocky and shallow while lower elevations tend towards silty clay soils derived from loess and the underlying bedrock (Fenneman, 1938 and USACE, 1968). In some areas, all topsoil has eroded (USACE, 1968).

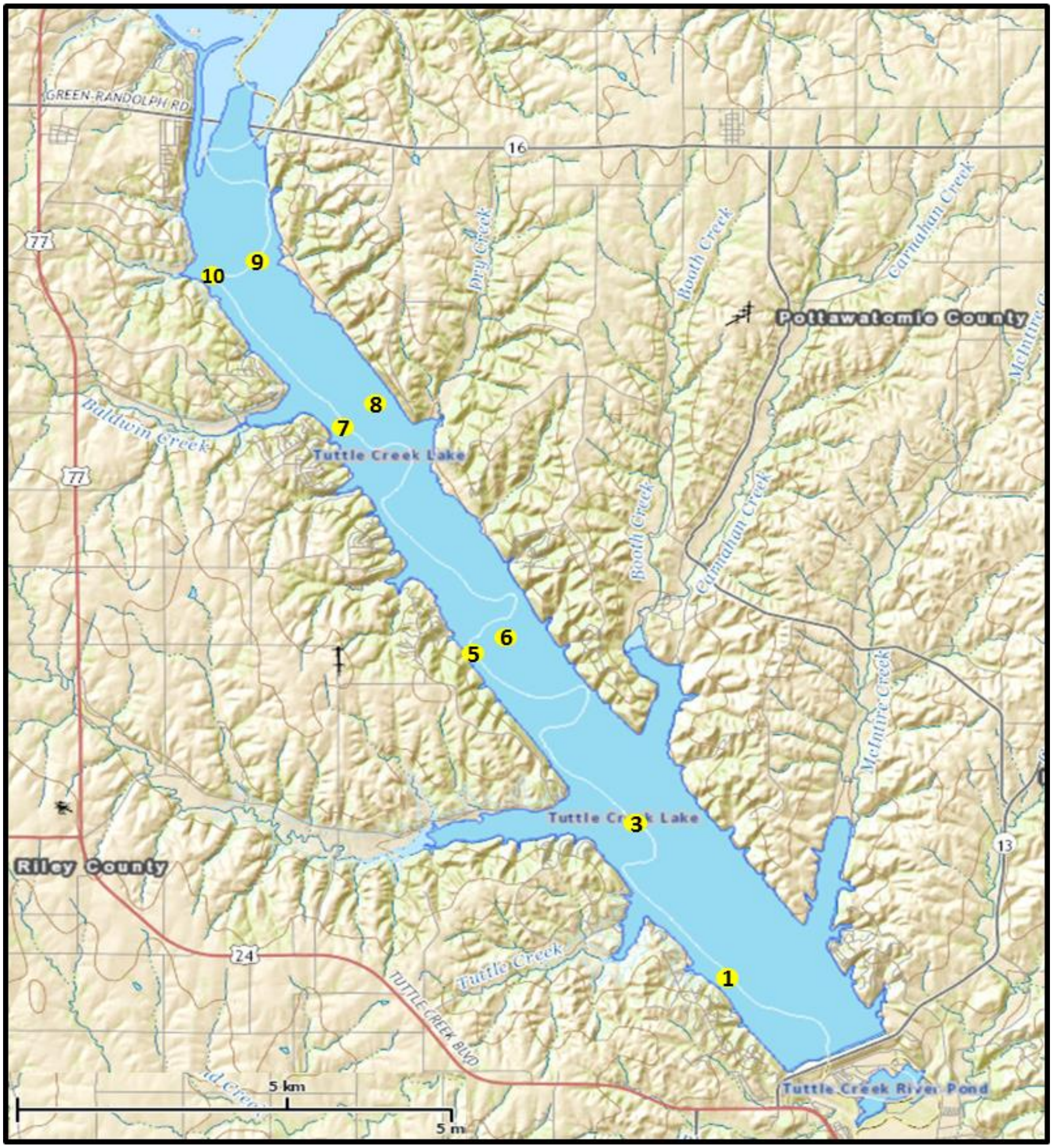

Figure 7. Tuttle Creek Lake with coring locations indicated (KBS, 2016).

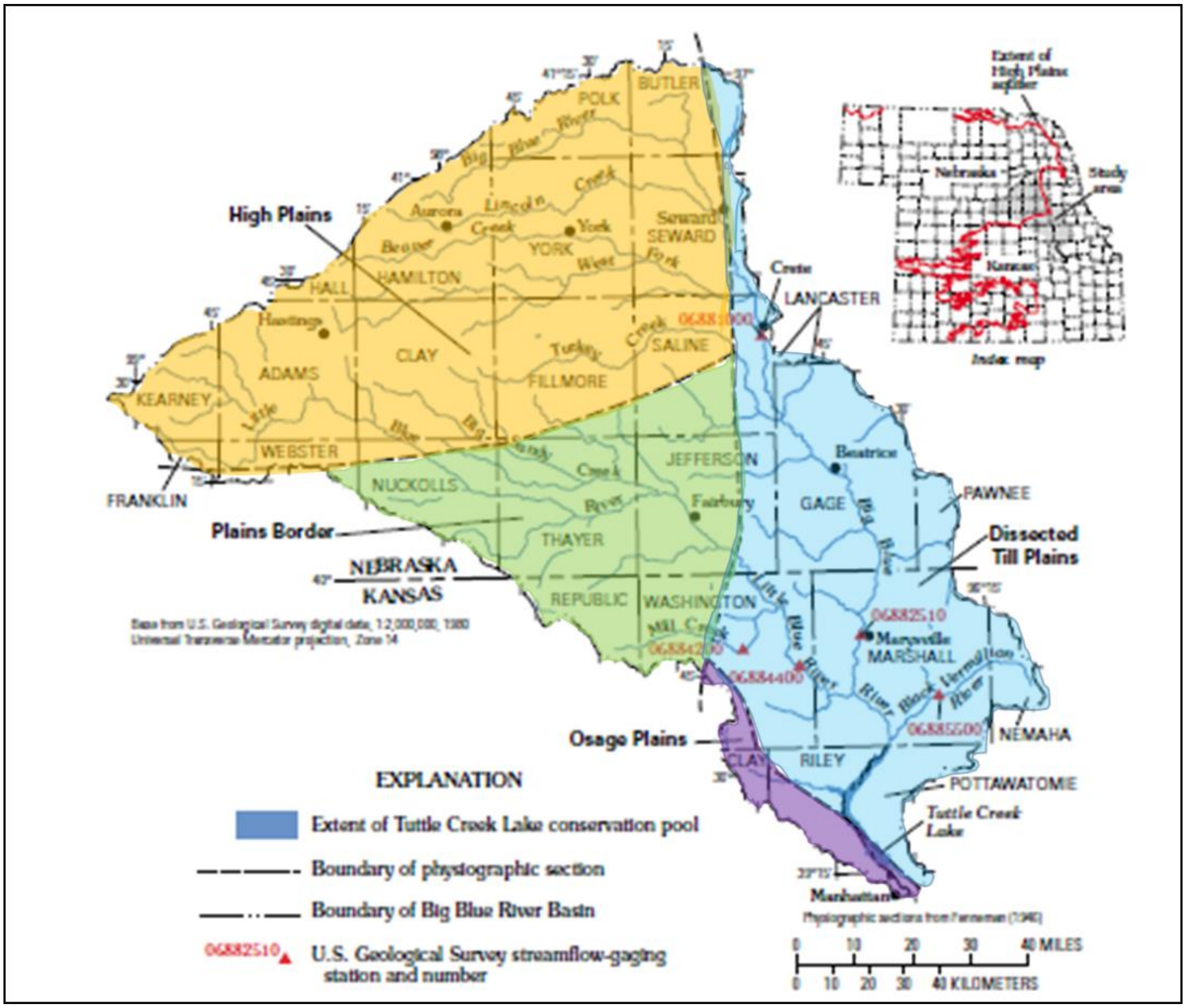

Figure 8. The Big Blue River basin (Adapted from Juracek, 2002).

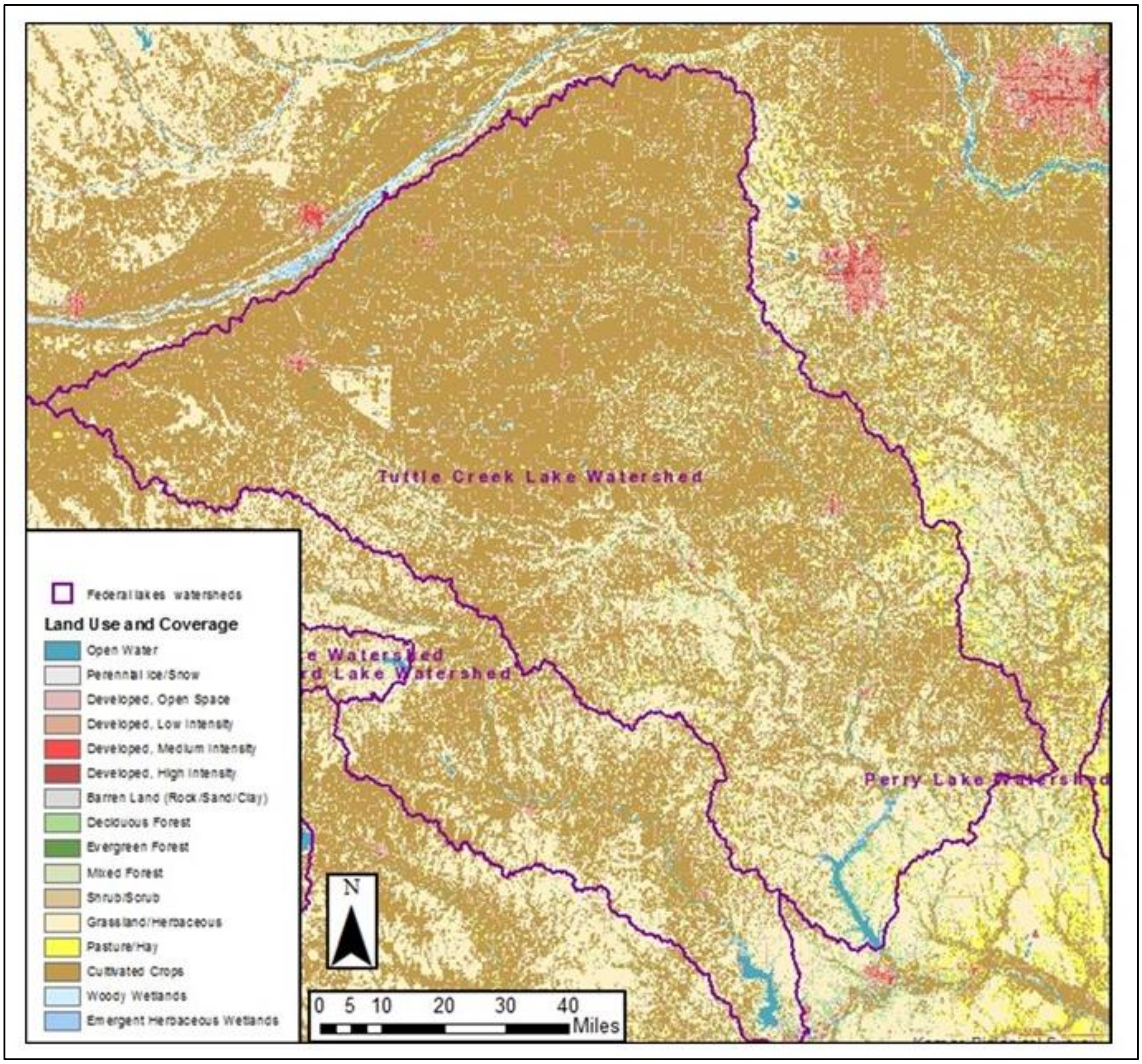

Figure 9. Land use in the Tuttle Creek Lake watershed (Adapted from USDA, 2014).

Chapter 4 - Methods

<u>Analysis of deep core samples and measurement of erodibility characteristics.</u>

In September 2015, USACE collected ten deep cores from Tuttle Creek Lake (Figure 7). These cores were numbered sequentially with increasing distance from the dam. Cores 2 and 4 were not provided for analysis in this report and their locations are unknown. For consistency with USACE's nomenclature, I kept the original numbering, omitting cores 2 and 4. Additionally, only one core was presented completely for analysis; other cores were missing at least one section. USACE personnel processed eight of the cores at the National Sedimentation Laboratory (NSL) at Oxford, Mississippi, in October 2015 using one of the NSL's Jet Erosion Tester (JET) devices. In this case, the Corps of Engineers used the "Big Jet" (Robert Wells, Personal Communication, 2016). This tester is made up of an impinging jet with a continuous water source, a tube to hold the testing system in place and ensure the sample is submerged in water, and a point gauge to measure the depth of scour in the sample being tested (Hanson and Cook, 2004) (Figure 11). Versions of this system can measure scour both *in situ* or in the lab. Cores ranged from 1.25 to 8.83 feet in length and each core was partitioned into approximately six inch sections for sampling in the JET. The number of samples tested in each core ranged from two to seven, for a total of 34 samples.

Hanson and Cook (2004) developed a Microsoft Excel spreadsheet routine to record and analyze JET data, which has since been adapted for use with other erosion testing methods using the JET (Daly *et al.*, 2013a). These adaptations include what is called the "iterative method" to estimate erosion parameters k_d and τ_c. Although this method remains unpublished, according to Robert Wells (2016) it is the method preferred by USACE and is the method used in this report.

Employing a plot of the original scour depth versus time, this method uses initial values of k_d and τ_c derived from the Blaisdell method and fitted to observed scour depth data. Using the Excel solver mechanism, the spreadsheet then calculates an upper limit for the critical shear stress to keep scour depths from surpassing the equilibrium scour depth. Concurrently, the solver searches for a solution for k_d and τ_c that minimizes the root-mean-square error between measured and predicted time (Simon *et al.*, 2010).

Following procedures in Hanson and Simon (2001) and Karmaker and Dutta (2010), I conducted statistical analysis on the JET tester results from the solver using Microsoft Excel 2010. To determine parameter relationships and overall erodibility, I conducted analysis on both critical shear stress and erodibility coefficients. Because USACE was primarily interested in the erodibility coefficients for their project, after classifying the erodibility of the samples I conducted further statistical analysis on the erodibility coefficient parameter only. To test the samples for locational and depth dependency, I conducted analysis of variance (ANOVA) analysis on each core and on grouped sets of depths, regardless of core. I used ArcMap to measure the distance from each sample site to the Tuttle Creek Dam outlet using sediment deposition patterns and characteristics discussed by Morris and Fan (1998) as a guide. USACE determined the sample sites, drawing five cores from the submerged Big Blue River channel and three outside of it. For in-channel sites, I followed the river channel from site to outlet as depicted in Figure 10. For out-of-channel sites, I followed the shortest distance perpendicular from the site to the river channel and followed the river channel to the outlet. To determine depth dependencies throughout the lake, I grouped the samples into four groups. Because Juracek and Mau (2002) determined that the lake's sediment is overwhelmingly silt and clay (98%), I could not base my groups on discernable layers in the sediment. Instead, I grouped the samples based on three continuous data gaps in the cores. These groups are shown in Table 1. Gaps between groups are 0.083 feet, 0.25 feet and 0.083 feet. These gaps represent depths for which there is no data in any core.

Group Number	Number Samples	Top Depth (ft)	Bottom Depth (ft)	Thickness (ft)	Maximum k_d (cm^3/N−s)	Minimum k_d (cm^3/N−s)
1	9	0.25	1.25	1.0	681.8	40.21
2	7	1.33	2.17	0.92	204.00	15.98
3	9	2.50	5.00	2.5	82.14	10.03
4	9	5.08	8.83	3.75	78.46	0.38

Table 1. Samples grouped by depth.

Mapping of sediment by erodibility and depth

To make the sediment map, I used the Corps of Engineers-provided Tuttle Creek Lake geotif created from a 2009 bathymetric survey using a NAD 1983 State Plane-North Kansas coordinate system. All subsequent layers were projected in this coordinate system. From this map I created a lake extent mask shapefile in order to limit data analysis to the lake only. Using the four groups of samples listed in Table 1, I plotted each group as a separate three-dimensional point feature class. I then conducted inverse distance weighting (IDW) and ordinary kriging analysis to interpolate the data and assess depth and distance dependent patterns in the erodibility of the sediment. Both methods of interpolation are commonly used in soil sciences (Lopez *et al.*, 2004; Robinson and Metternicht, 2004). However, because IDW relies on nearness of neighbors to be effective and is sensitive to errors in its edge areas, I conducted analysis only on the maps produced through ordinary kriging due to the small number of samples in each group and the distances between them (Yasrebi *et al.*, 2009). All geostatistical analysis and map production was done in ArcMap 10.3.1.

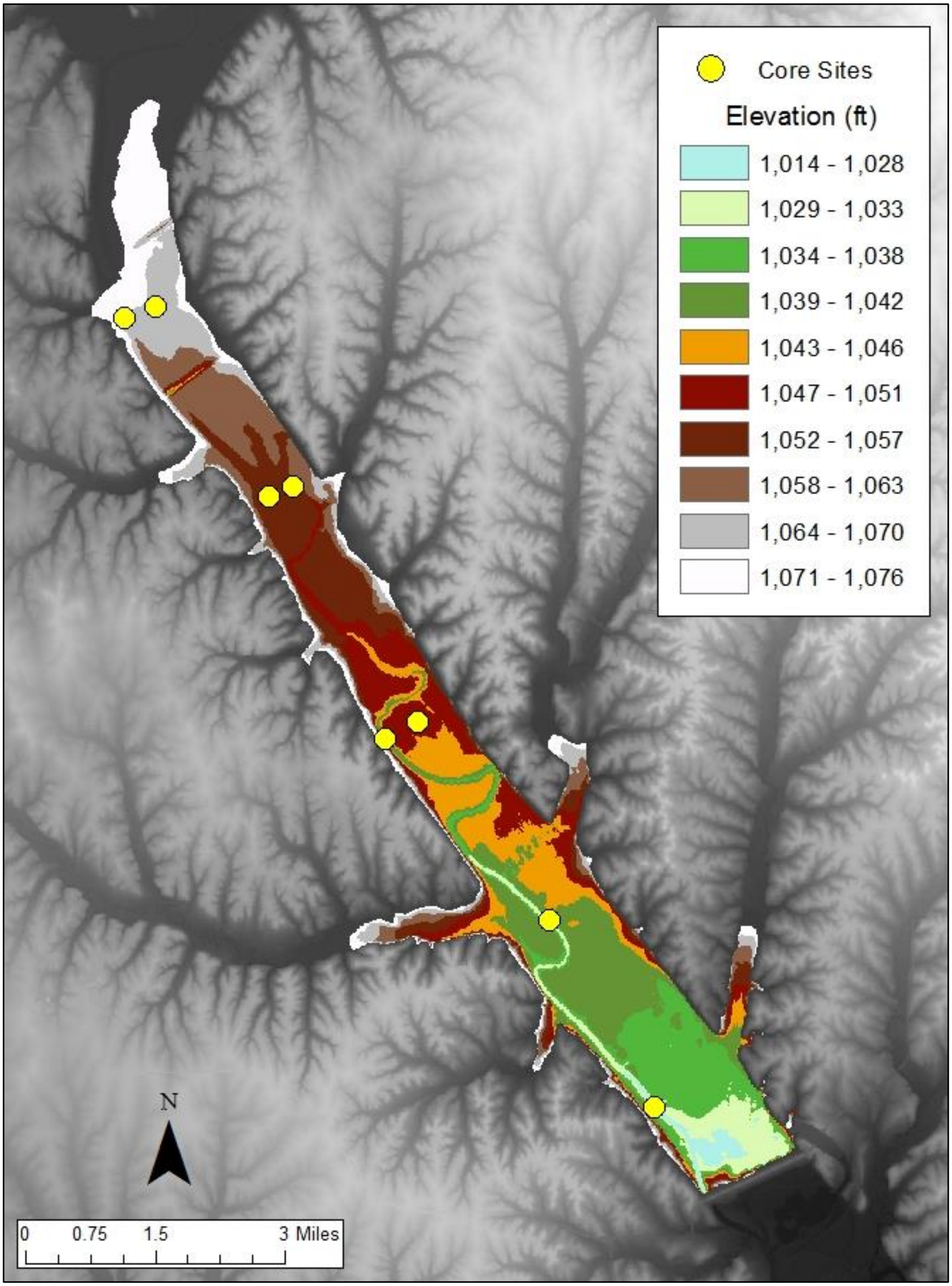

Figure 10. Lake elevation with coring sites indicated (Adapted from USACE, 2015).

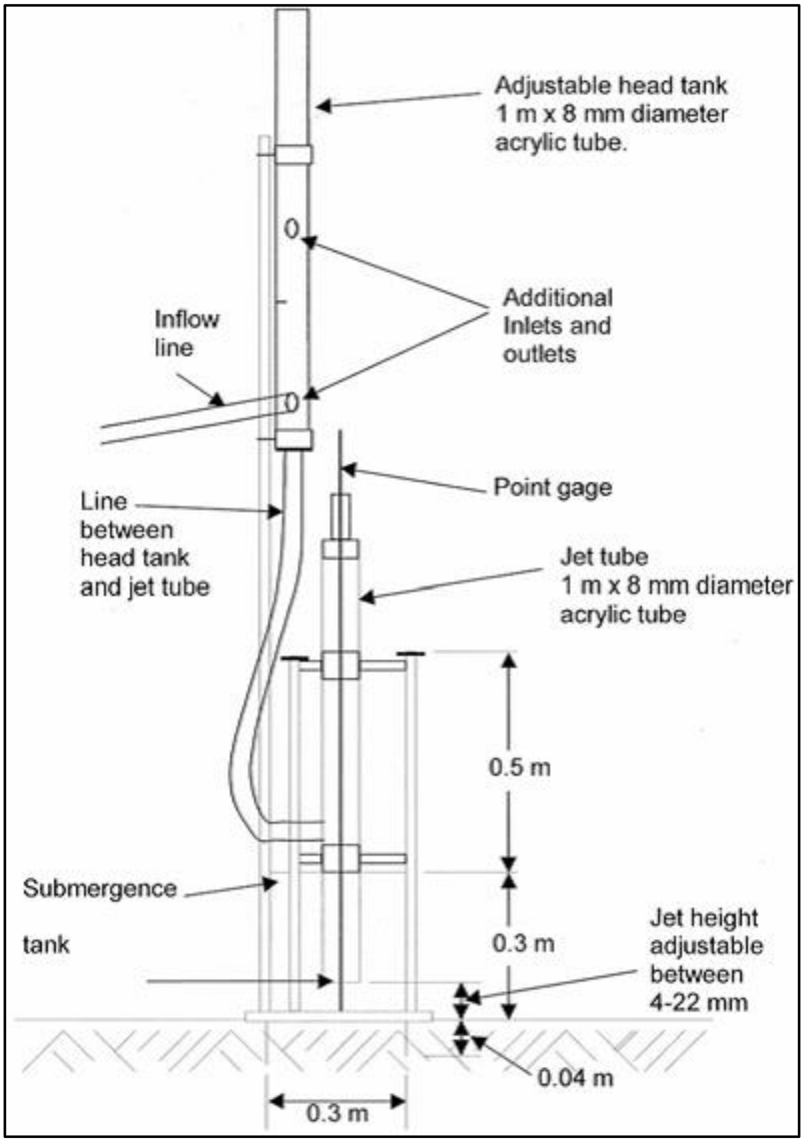

Figure 11. Jet Erosion Tester device (Simon *et al.*, 2011, adapted from Hanson and Simon, 2001).

Chapter 5 - Results and Discussion

Jet Testing

The relative frequencies of k_d and τ_c values are shown in Figures 12 and 13, respectively. Results for the erodibility coefficient show that the sediments tested in Tuttle Creek Lake fall between 0.1 and 1000 $cm^3/(N\text{-}s)$, with all but one falling above 1 $cm^3/(N\text{-}s)$ and all but five falling above 10 $cm^3/(N\text{-}s)$. These high values suggest high erodibility throughout Tuttle Creek Lake with higher values found in those cores originating in the submerged river channel and smaller values found in the submerged floodplain. These differences in values also indicate that the Big Blue River channel is active the length of the lake 54 years after the reservoir filled. The differences in the erodibility values between the former channel and former flood plain suggest that there different processes occurring in the submerged channel and submerged floodplain. Although it is not possible to explain what the processes are based on this study, the differences in sediment erodibility suggests that conditions that affect erodibility are different in the former channel and former floodplain. All critical shear stress values fall between 0.1 and 10 Pa, with most falling between 1 and 10 Pa, again indicating highly erodible material. Analysis indicates that there is not a wide variety of erosion resistance of the lake, even as values vary within each sediment core.

Previous studies done with the jet (Karmaker and Dutta, 2010; Hanson and Simon, 2001; Hanson and Hunt, 2007) clearly showed an inverse relationship between critical shear stress and erodibility coefficient. The results presented here indicate that k_d and τ_c have the following relationship:

$$k_d = 21.1\tau_c^{1.354} \quad (5)$$

which is at odds with findings from similar previous studies conducted and indicates that these erodibility parameters do not follow an inverse relationship (Figure 14). However, comparing scatter plots of critical shear stress and erodibility coefficients from this study to those presented in Hanson and Simon (2001) and Karmaker and Dutta (2010) suggests that the considerably higher erodibility coefficients and considerably lower critical shear stress values found in this study change the nature of the k_d -τ_c relationship. Plotting these parameters in a classification scatter plot illustrates that two points are classified as erodible while the rest are classified as very erodible, following Hanson and Simon (2001) (Figure 15). Both samples from the erodible classification are from Core 10.

ANOVA analysis conducted on the erodibility coefficient for site dependency showed a very low p-value ($p = 4.72 \times 10^{-15}$), indicating that locations on the lake (upstream or downstream) vary in terms of erodibility. Similar analysis on the depth layers also showed a low p-value ($p = 0.000467$), also indicating variability in erodibility at depth. This is shown in Figures 16 and 17. Plotting distance against erodibility and fitting an exponential trendline gave an R^2 value of 0.12, which indicates there is a relationship (Figure 18); plotting depth against erodibility yielded an R^2 of 0.52, which indicates that the relationship between erodibility and depth is stronger than that between erodibility and the distance from the dam (Figure 19).

Lake Sediment Maps

Geospatial analysis of the sediments confirmed the depth and distance variation in the sediment erodibility in Tuttle Creek Lake, with downstream and shallow-depth areas expected to have higher erodibility than areas upstream or at greater depth (Figures 20-23). Because of the differing core lengths, not all cores were represented at each depth layer. Additionally, no flood plain cores near the dam were available for analysis, causing some bias towards the more erodible in-channel conditions.

Discussion

Unlike findings from previous studies, the relationship between critical shear stress and erodibility coefficient does not appear to be inverse, nor does it show that there is much of a relationship at all. Plotting the data in this study on the same axes as Hanson and Simon (2004) and Karmaker and Dutta (2011) shows that the data in this study does potentially conform to the relationship established in the literature.

I believe that this study was hampered by too few sediment cores which resulted in too few individual samples for analysis. Although cores were spatially evenly distributed over the length of the lake, the large surface area of the lake meant that most cores were over a mile away from their nearest up- or downstream neighbor. The original sampling design for this study called for 12 sediment cores divided into 60 individual samples, nearly doubling the amount of samples. The depth of the cores could also give an inaccurate depiction of the characterization of the erodibility over extent of the lake. The deepest core was 8.83 feet deep; the deepest sediments in the study area are over 29 feet deep (Juracek and Mau, 2002). The area of deeper sedimentation coincided with the most upstream portions of the study area. If the trend of decreasing erodibility with increasing distance from the dam and depth applies to the deeper sediments, then the least erodible areas of the sediment remain unstudied.

Given the indicators for highly erodible sediment present in the watershed, the findings presented here do not seem unusual. Perry Lake shares several common characteristics with Tuttle Creek Lake. This reservoir's watershed, although 1/8th size of Tuttle Creek Lake's watershed, drains the Dissected Till Plains, a high erosion physiographic section also found in the areas of highest sediment loads in Tuttle Creek Lake's watershed (Fenneman, 1938). Perry Lake has a watershed almost entirely of glacial till and clay-sized soil particles (USACE, 1972). Also like Tuttle Creek Lake, Perry Lake is the sole large impoundment in its watershed. Perry Lake also experiences high sedimentation rates, although not as high that found in Tuttle Creek Lake. At 18%, it is high enough to shorten the practical lifespan of the dam considerably (KWO, 2010). Although the land use has greater percentages of land dedicated to pasture and grassland, Perry Lake's watershed also is rural and agricultural (USDA, 2014).

Perry Lake's sediment allocation is not filling up as quickly as Tuttle Creek Lake's allocation and no literature has been published on its erodibility. Because of the similarities presented here, Tuttle Creek Lake's erodibility characteristics could also reasonably serve as a predictor for erodibility of Perry Lake sediment.

The situation at Milford Lake appears different from that at Tuttle Creek and Perry Lakes. Although it has a much larger watershed than Tuttle Creek Lake, it is close in size to Tuttle Creek Lake. However, its sedimentation rate is just over half of its designed sediment rate (USACE, 1976; KWO, 2010). This reservoir is an impoundment of the Republican River and has seven federal reservoirs upstream, which do impact the sediment load in the river below these dams. Monitoring along the Republican River between the Kansas-Nebraska border and Milford Lake found that tributaries account for about 16% of sediment input into the river, suggesting that the remaining sediment must come from adjacent bank/land (KWO, 2010). Additionally, the sites found that 8% of sediment originates in Nebraska, while the remainder originates in Kansas. The same report concluded that the main stem streambanks and adjacent land contribute more to the sediment load than the tributaries, although none are high by Kansas state standards (KWO, 2010). Although the soils in the watershed are similar in size and composition to the soils, the Milford Lake watershed below the upstream impoundments falls in the High Plains and Plains Border Sections, which aren't as erodible as the Dissected Till Plains found in the Tuttle Creek Lake and Perry Lake watersheds (Fenneman, 1938). The Milford Lake watershed also experiences less precipitation than the Tuttle Creek Lake and Perry Lake watersheds, resulting in less overland erosion even though crops and pasture are the dominant land uses (PRISM, 2015; USDA, 2014). Clearly, there are some differences in erodibility of the soils in the Milford Lake and that of Tuttle Creek Lake. In this instance, Tuttle Creek Lake's erodibility parameters might not be a valid predictor of erodibility.

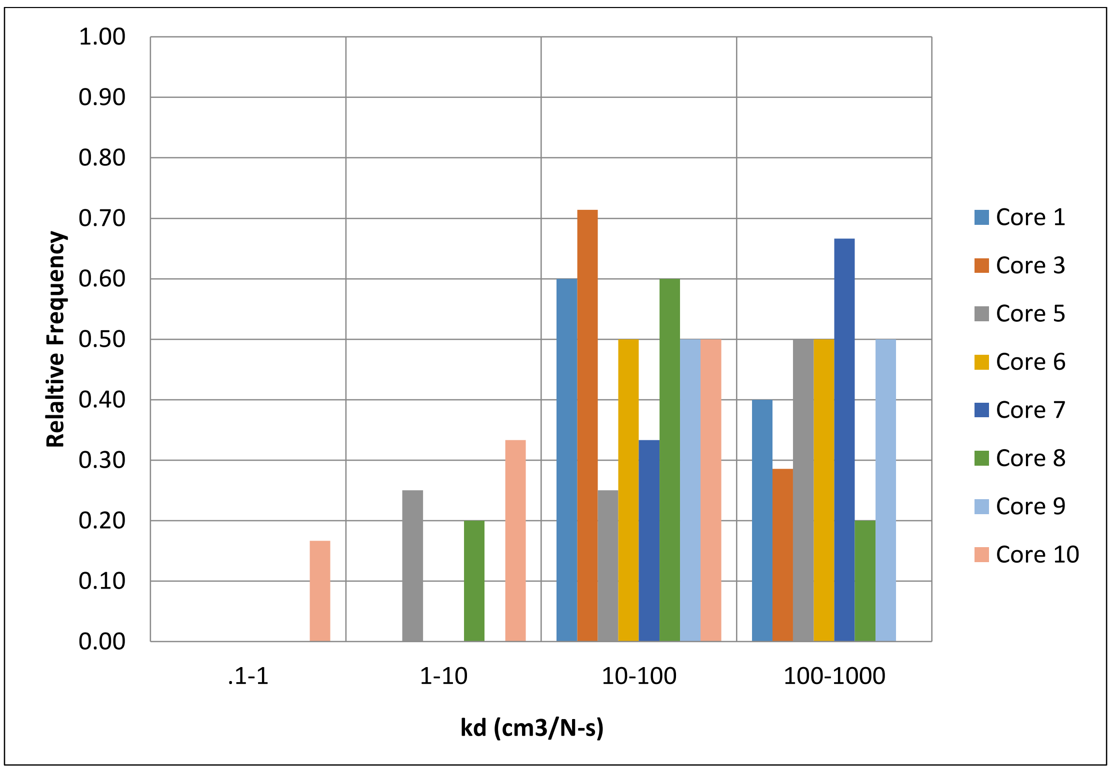

Figure 12. Relative frequency of erodibility coefficients.

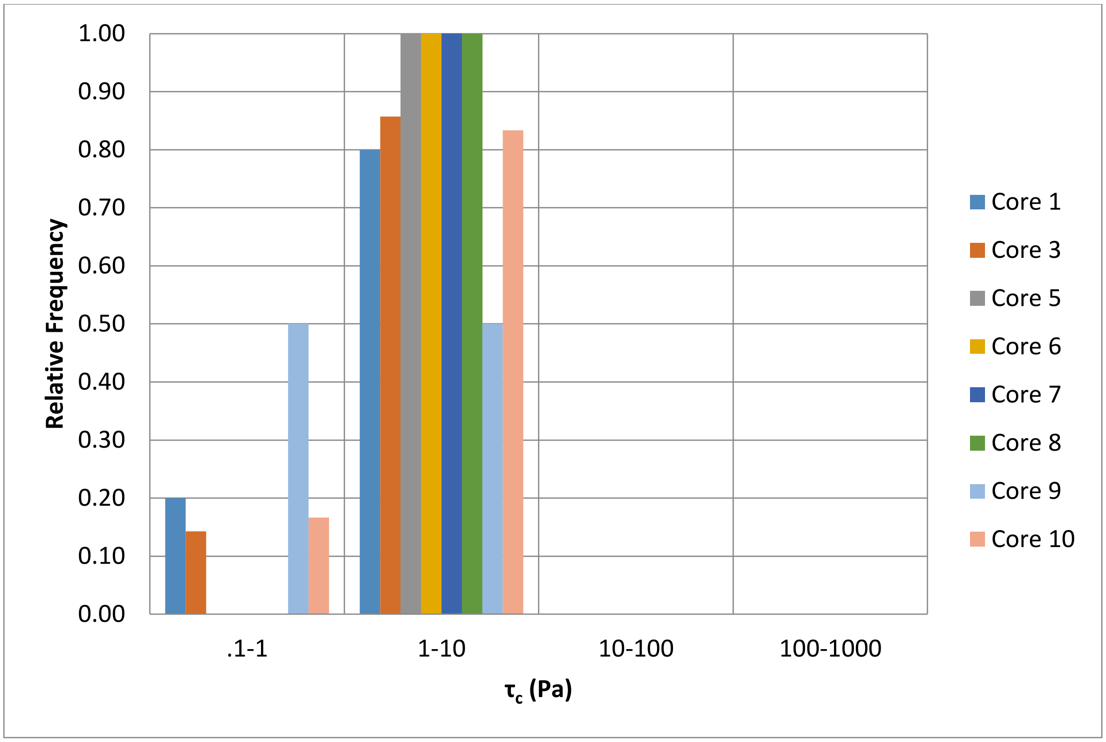

Figure 13. Relative frequency of critical shear stress.

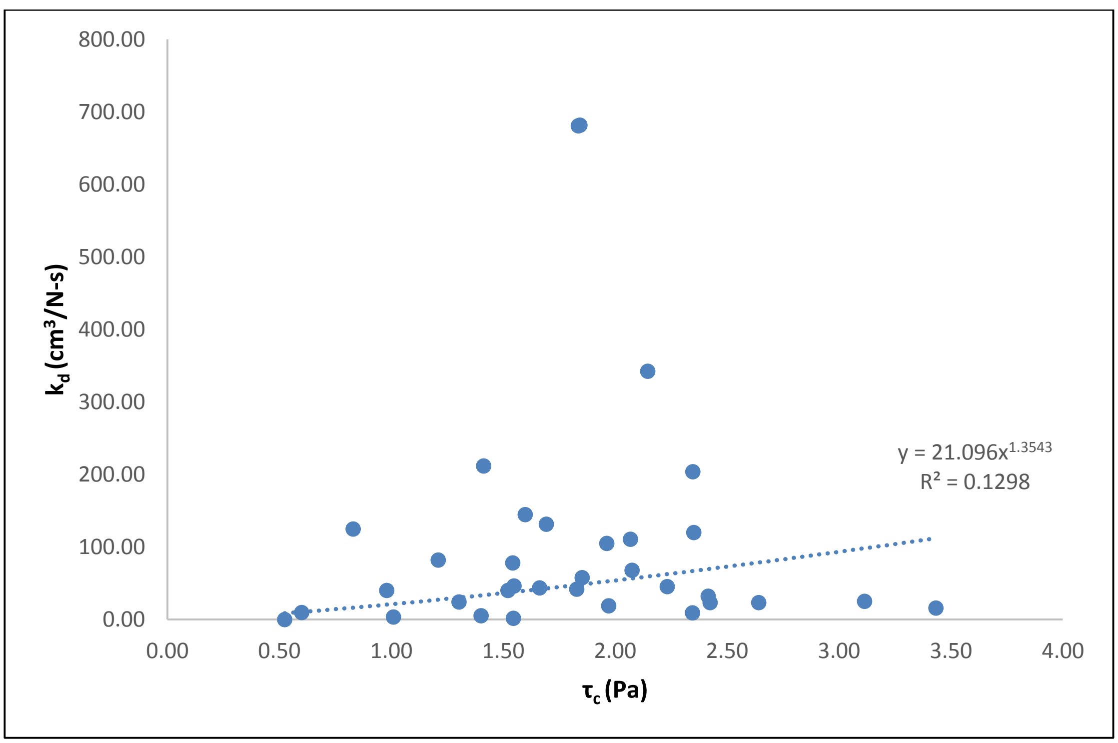

Figure 14. Scatter plot of critical shear stress v. erodibility coefficient.

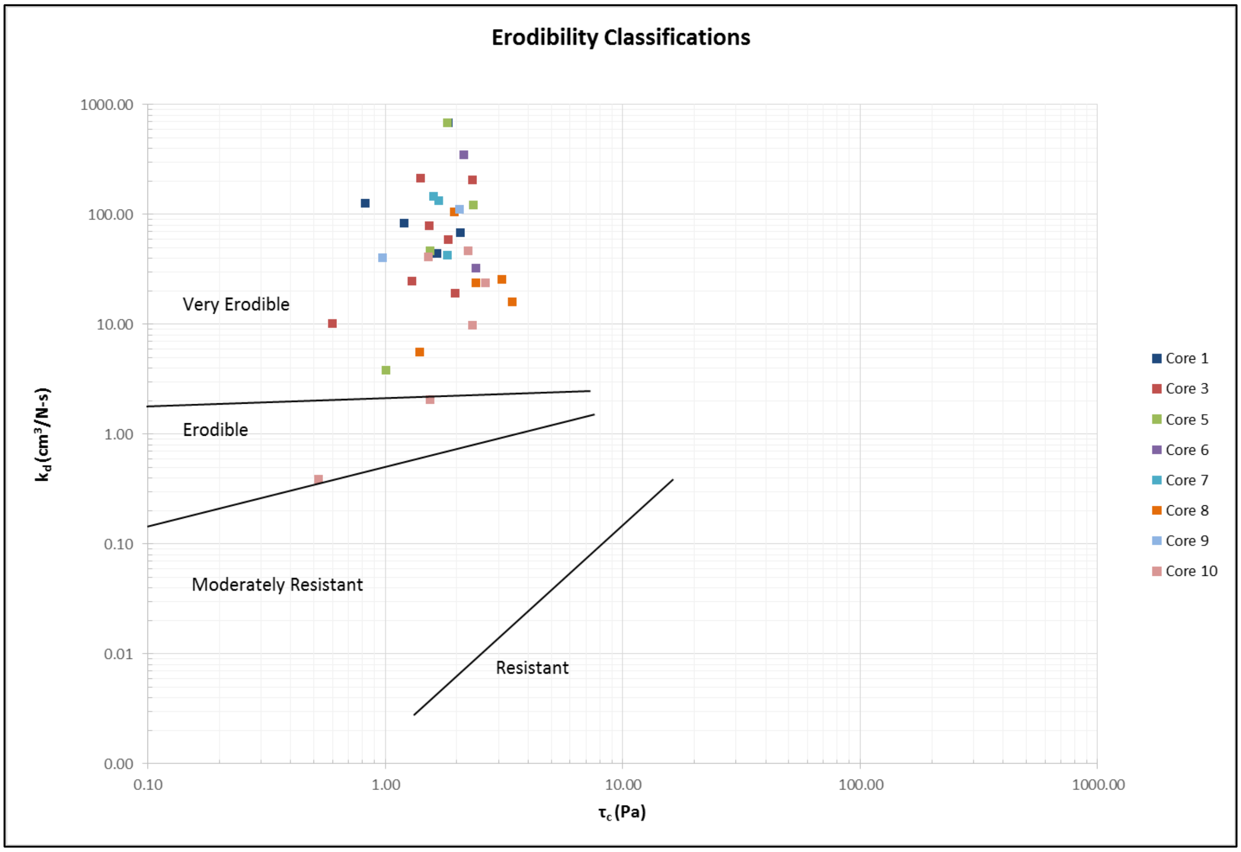

Figure 15. Erodibility classification of Tuttle Creek Lake sediment (after Hanson and Simon, 2001).

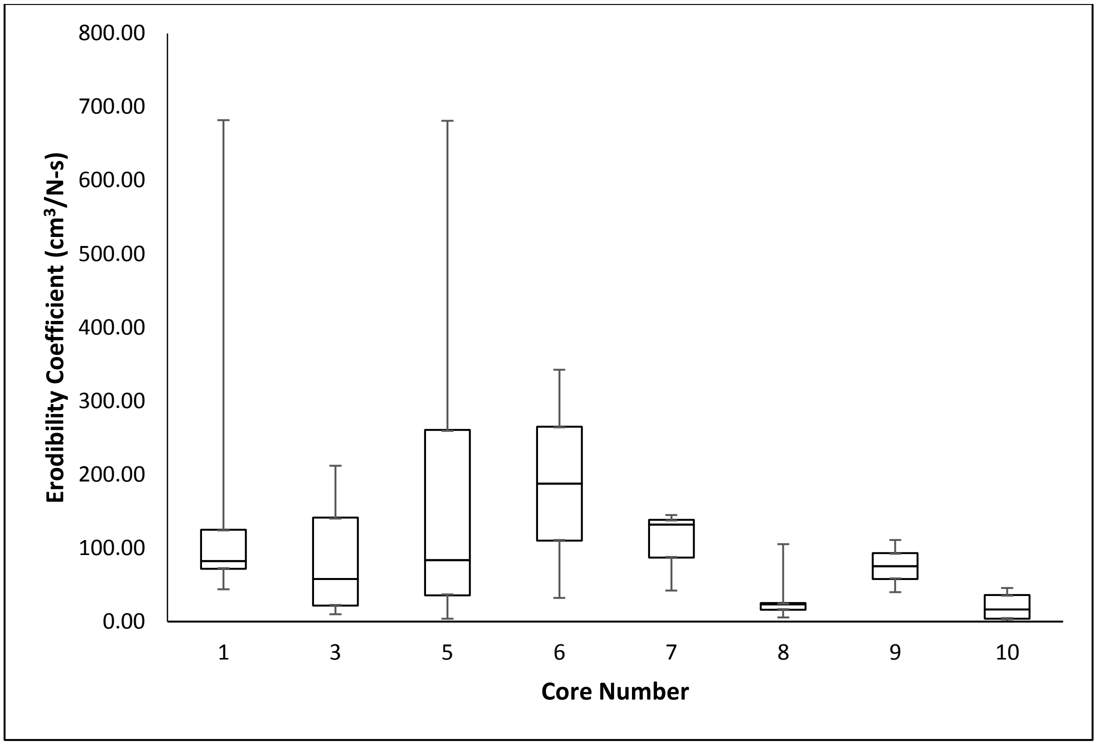

Figure 16. Box plot of spatial variation by sample site.

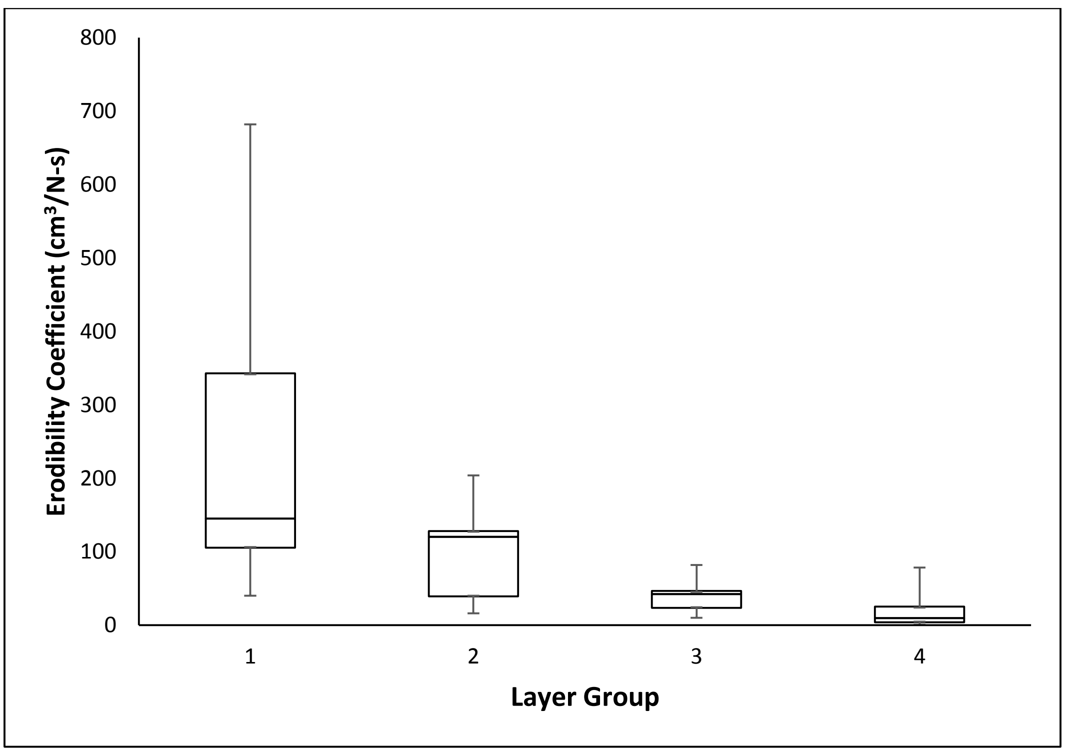

Figure 17. Box plot of spatial variation by depth layer.

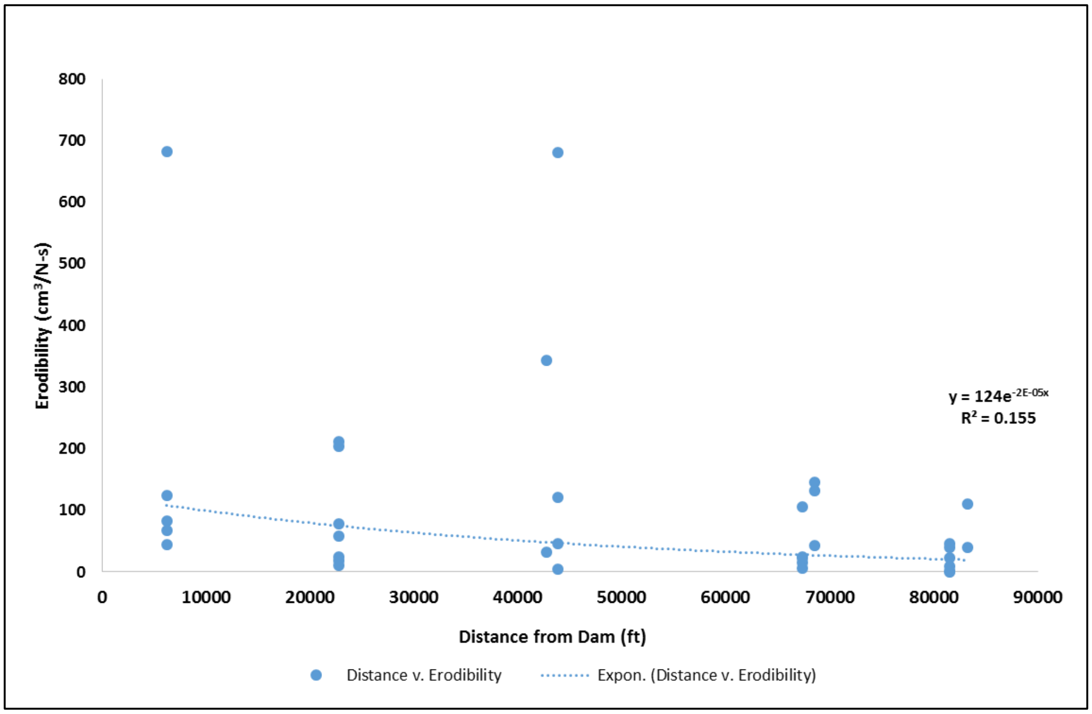

Figure 18. Scatter plot of erodibility as function of distance.

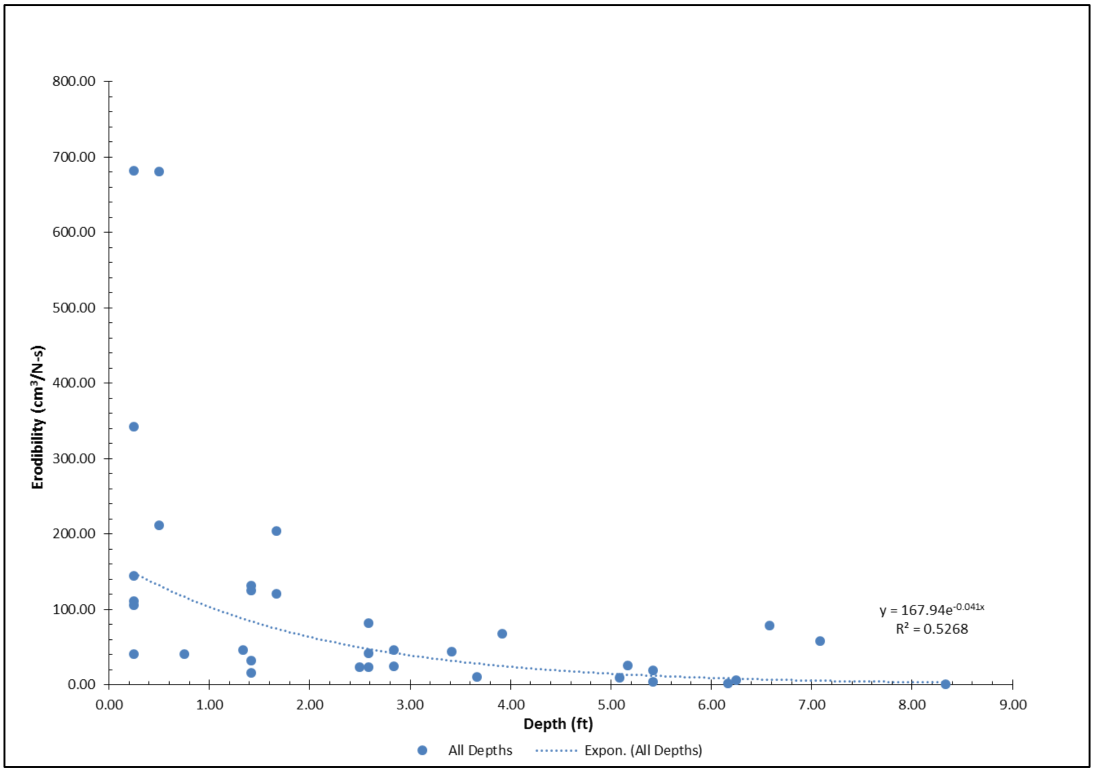

Figure 19. Erodibility as a function of depth below lake bed, measured from the top of each sample.

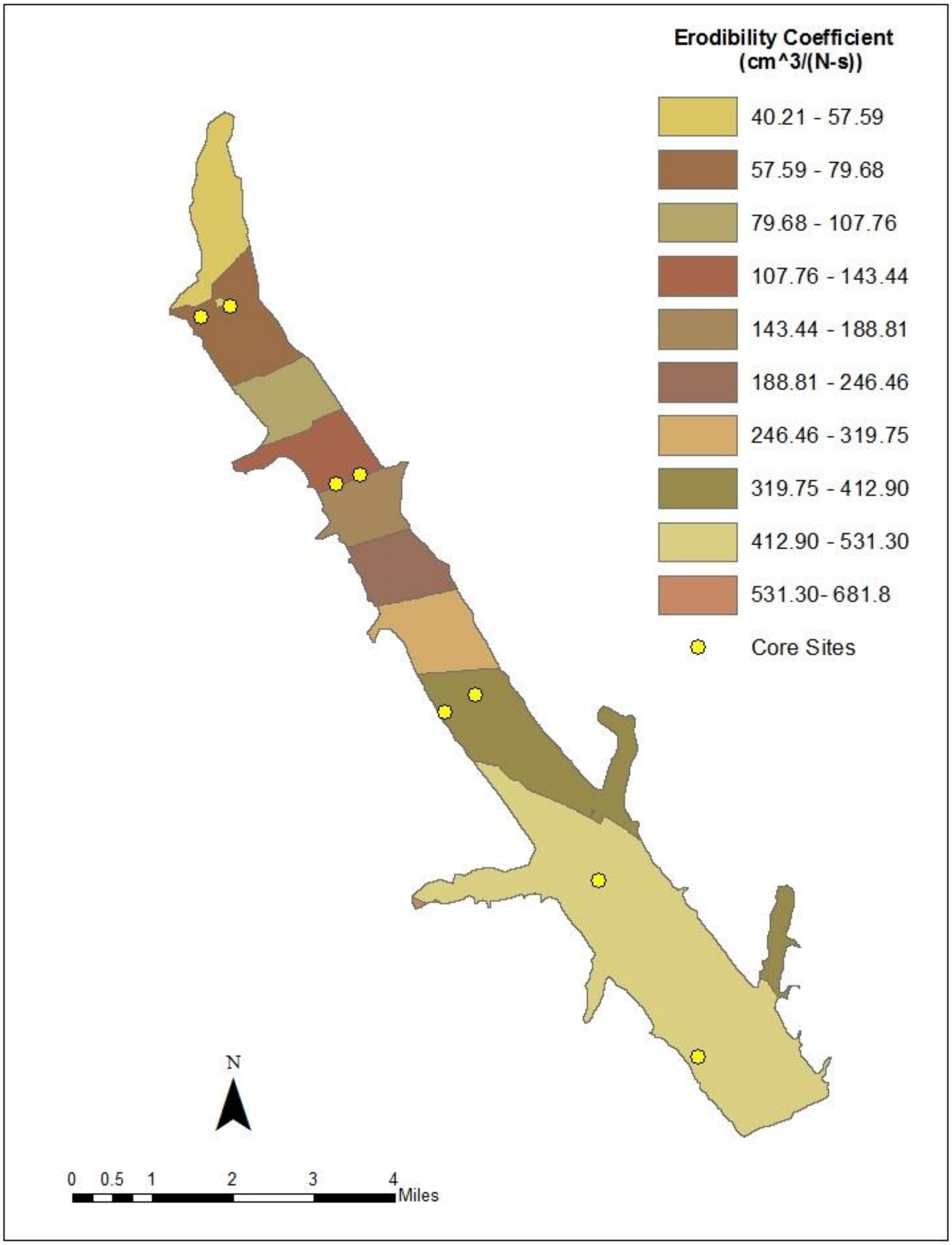

Figure 20. Tuttle Creek Lake erodibility at 0.25’ - 0.75’ depth.

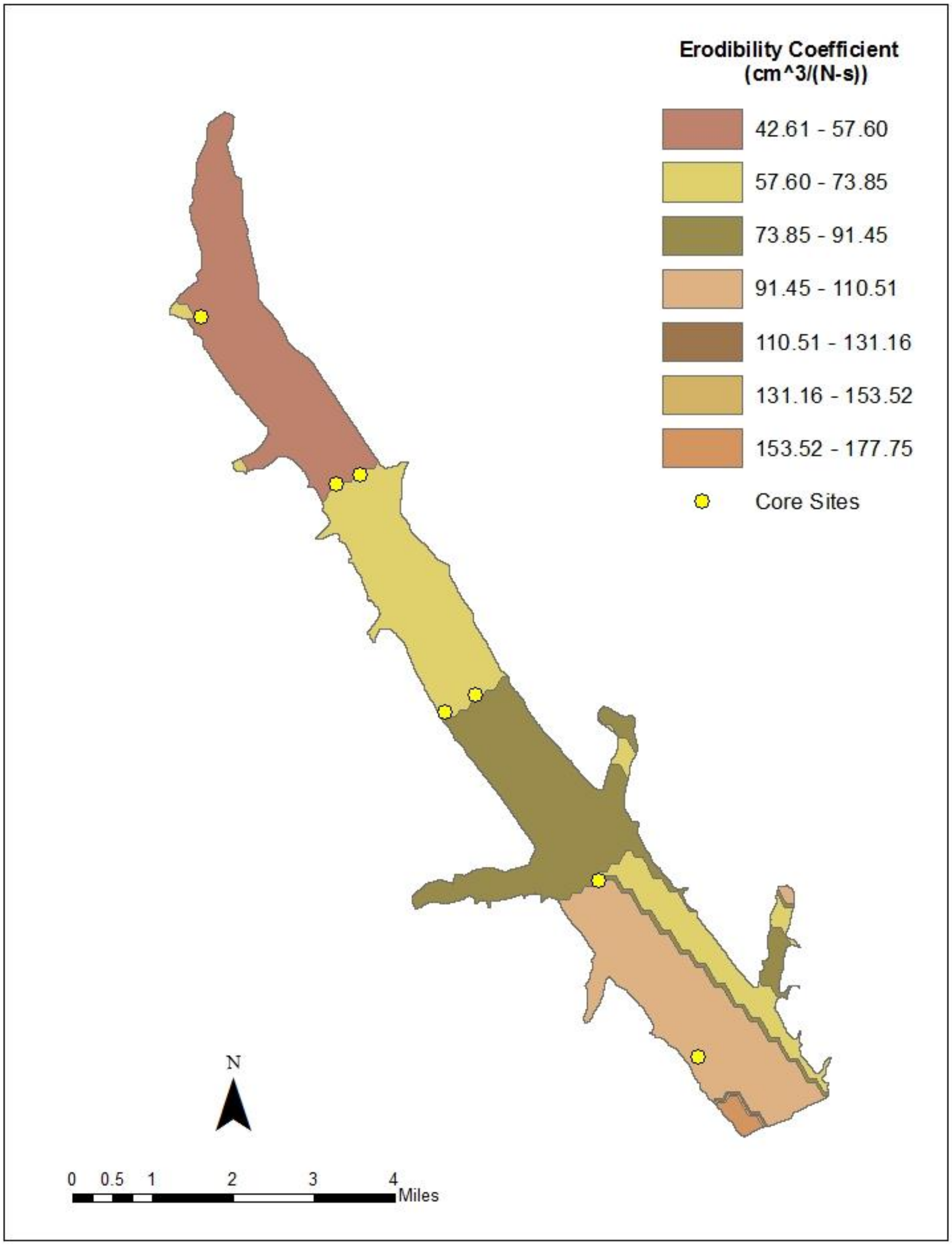

Figure 21. Tuttle Creek Lake erodibility at 1.33' - 2.25' depth.

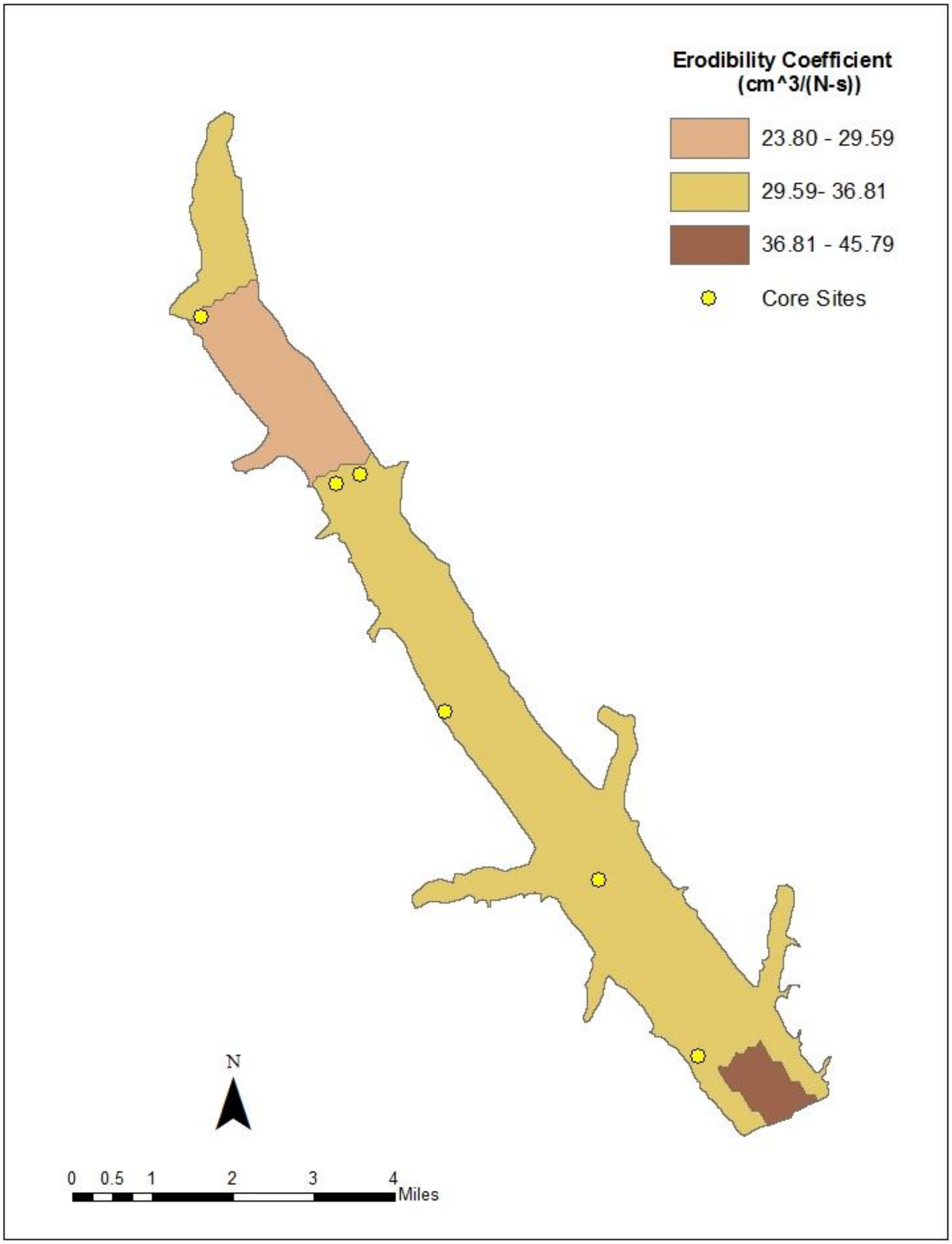

Figure 22. Tuttle Creek Lake erodibility at 2.50' - 5.00' depth.

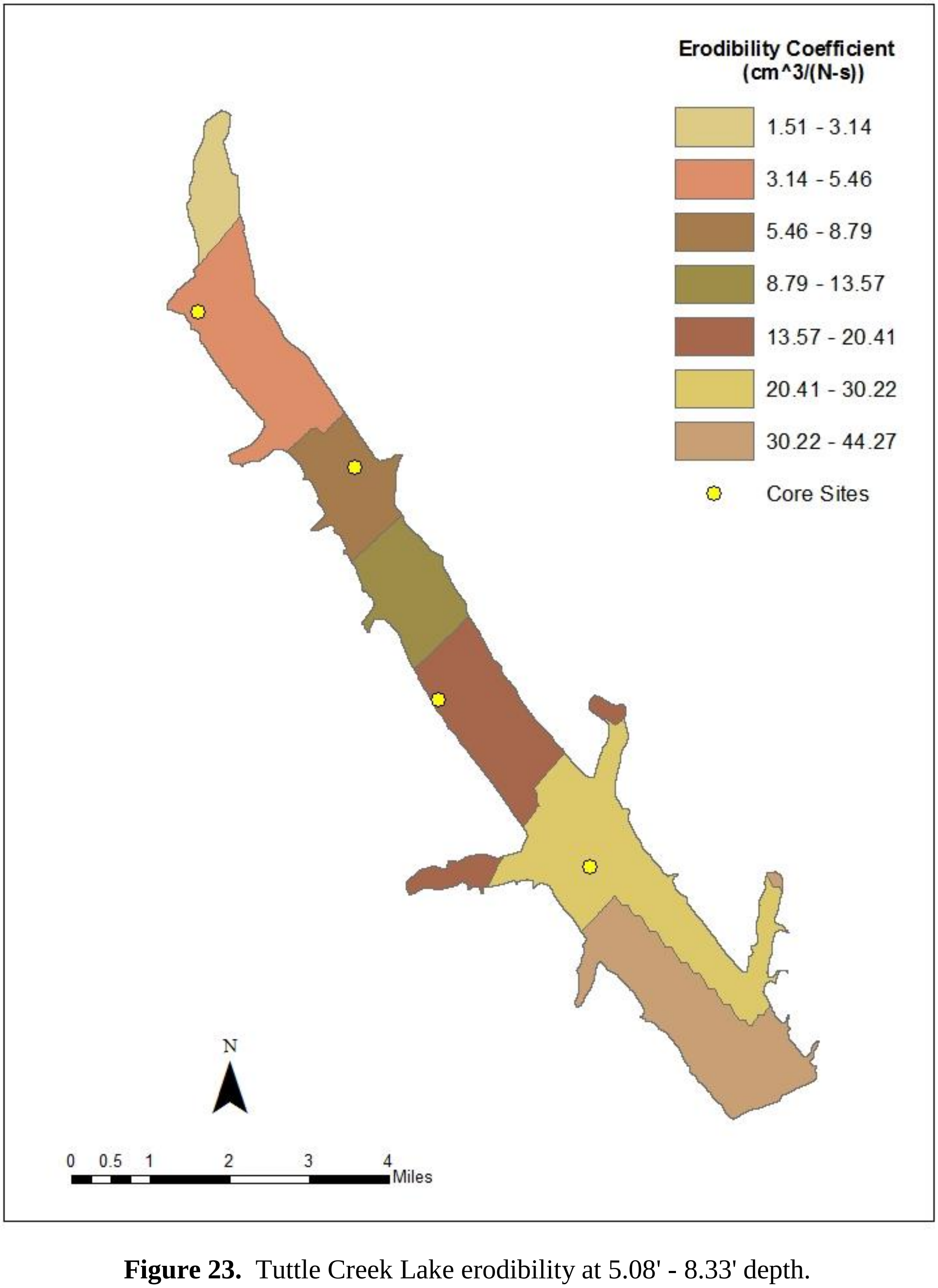

Figure 23. Tuttle Creek Lake erodibility at 5.08' - 8.33' depth.

Chapter 6 - Conclusion

Every reservoir is unique and operators must weigh many factors when considering near- and long-term management strategies for any given reservoir. Physical, chemical, and spatial sediment characteristics all have a role in how difficult or easy it will be to dislodge any given particle and where that particle will go once it moves. This study examined the spatial variability of two erosion parameters—the critical shear stress and erodibility coefficient—at Tuttle Creek Lake near Manhattan, Kansas.

All 34 sediment samples collected from the eight cores were classified as erodible or very erodible, even at depths of nearly nine feet below the lakebed. However, erodibility decreases with depth below the lake bottom and the distance from the lake bottom to the floor of the original valley is much greater than nine feet over much of the lake's extent. It is plausible that erosion-resistant layers of sediment exist at greater depths in Tuttle Creek Lake that were not reached by the cores used in this study. While sample size limits the conclusions in this report and more study should be conducted, the results could be applicable to predicting erodibility in other reservoirs located in regions with highly erodible soils or high erosion rates, such as Perry Lake.

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Appendix A - JET Output Data

Core	Sample	Top (ft)	Bottom (ft)	Thickness (ft)	Elevation (ft)	Top Elevation (ft)	Bottom Elevation (ft)	Total Core Depth (ft)	Critical Shear Stress (Pa)	Erodibility Coefficient (cm^3/(N-s)	Longitude	Latitude	Lake Water Depth (ft)	Distance from Dam (ft)
1	1.1	0.25	0.75	0.50	1026.9	1026.65	1026.15	4.42	1.84	681.80	-96.61	39.27	48	6195
1	1.2	1.42	1.92	0.50	1026.9	1025.48	1024.98	4.42	0.83	124.89	-96.61	39.27	48	6195
1	1.3	2.58	3.08	0.50	1026.9	1024.32	1023.82	4.42	1.21	82.14	-96.61	39.27	48	6195
1	1.4	3.42	3.92	0.50	1026.9	1023.48	1022.98	4.42	1.66	43.85	-96.61	39.27	48	6195
1	1.5	3.92	4.42	0.50	1026.9	1022.98	1022.48	4.42	2.08	68.18	-96.61	39.27	48	6195
3	3.1	0.50	1.00	0.50	1031.9	1031.40	1030.90	7.58	1.41	211.95	-96.64	39.30	43	22780
3	3.2	1.67	2.17	0.50	1031.9	1030.23	1029.73	7.58	2.35	204.00	-96.64	39.30	43	22780
3	3.3	2.83	3.33	0.50	1031.9	1029.07	1028.57	7.58	1.30	24.54	-96.64	39.30	43	22780
3	3.4	3.67	5.00	1.33	1031.9	1028.23	1026.90	7.58	0.60	10.03	-96.64	39.30	43	22780
3	3.5	5.42	5.92	0.50	1031.9	1026.48	1025.98	7.58	1.97	19.10	-96.64	39.30	43	22780
3	3.6	6.58	7.08	0.50	1031.9	1025.32	1024.82	7.58	1.54	78.46	-96.64	39.30	43	22780
3	3.7	7.08	7.58	0.50	1031.9	1024.82	1024.32	7.58	1.85	58.05	-96.64	39.30	43	22780
5	5.1	0.50	1.00	0.50	1039.9	1039.40	1038.90	5.92	1.84	680.92	-96.67	39.33	35	43846
5	5.2	1.67	2.17	0.50	1039.9	1038.23	1037.73	5.92	2.35	120.40	-96.67	39.33	35	43846
5	5.3	2.83	3.33	0.50	1039.9	1037.07	1036.57	5.92	1.55	46.52	-96.67	39.33	35	43846
5	5.4	5.42	5.92	0.50	1039.9	1034.48	1033.98	5.92	1.01	3.82	-96.67	39.33	35	43846
6	6.1	0.25	0.75	0.50	1046.9	1046.65	1046.15	1.92	2.15	342.69	-96.66	39.34	28	42766
6	6.2	1.42	1.92	0.50	1046.9	1045.48	1044.98	1.92	2.42	32.37	-96.66	39.34	28	42766
7	7.1	0.25	0.75	0.50	1050.9	1050.65	1050.15	3.08	1.60	144.96	-96.70	39.37	24	68556
7	7.2	1.42	1.92	0.50	1050.9	1049.48	1048.98	3.08	1.69	131.66	-96.70	39.37	24	68556
7	7.3	2.58	3.08	0.50	1050.9	1048.32	1047.82	3.08	1.83	42.18	-96.70	39.37	24	68556
8	8.1	0.25	0.75	0.50	1056.9	1056.65	1056.15	6.75	1.96	105.34	-96.69	39.38	18	67402
8	8.2	1.42	1.92	0.50	1056.9	1055.48	1054.98	6.75	3.43	15.98	-96.69	39.38	18	67402
8	8.3	2.58	3.08	0.50	1056.9	1054.32	1053.82	6.75	2.43	23.64	-96.69	39.38	18	67402
8	8.4	5.17	5.67	0.50	1056.9	1051.73	1051.23	6.75	3.12	25.20	-96.69	39.38	18	67402
8	8.5	6.25	6.75	0.50	1056.9	1050.65	1050.15	6.75	1.40	5.57	-96.69	39.38	18	67402
9	9.1	0.25	0.75	0.50	1067.9	1067.65	1067.15	1.25	2.07	110.77	-96.72	39.41	7	83257
9	9.2	0.75	1.25	0.50	1067.9	1067.15	1066.65	1.25	0.98	40.21	-96.72	39.41	7	83257
10	10.1	0.25	0.75	0.50	1067.9	1067.65	1067.15	8.83	1.52	40.56	-96.73	39.40	7	81568
10	10.2	1.33	2.25	0.92	1067.9	1066.57	1065.65	8.83	2.23	45.83	-96.73	39.40	7	81568
10	10.3	2.50	3.00	0.50	1067.9	1065.40	1064.90	8.83	2.64	23.55	-96.73	39.40	7	81568
10	10.4	5.08	5.58	0.50	1067.9	1062.82	1062.32	8.83	2.35	9.66	-96.73	39.40	7	81568
10	10.5	6.17	6.67	0.50	1067.9	1061.73	1061.23	8.83	1.55	2.06	-96.73	39.40	7	81568
10	10.6	8.33	8.83	0.50	1067.9	1059.57	1059.07	8.83	0.52	0.38	-96.73	39.40	7	81568

Notes:

1. Cores are numbered in accordance with USACE numbering. Sample numbers are derived from the core number and the individual sample within the core as measured from the top. In core one, sample 1.1 would be the top six inches of the core while sample 1.5 would be the bottom six inches of the core.

2. The Top (ft) column represents top of the individual sample as measured from the top of the core. All cores were trimmed prior to analysis so no "Top" value is from the lakebed-water interface. The Bottom (ft) column represents the bottom of the individual sample as measured from the top of the core. For example, sample 1.2, a six inch section of core 1, can be found at 1.42-1.92 feet depth of the core.

3. Critical shear stress and erodibility coefficient data are derived from the JET spreadsheet routine.