INVESTIGATION OF SUSPENDED-SEDIMENT CONCENTRATION IN THE

MISSISSIPPI RIVER USING LASER DIFFRACTION AND

REMOTE SENSING SURROGATE METHODS

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Dedication

I dedicate this thesis to my parents, Mamie and Hilly, and my sister, Ninon, for encouraging me and always being proud of my accomplishments. Without their continuous and relentless support, my education at Saint Louis University would not be possible.

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CHAPTER 1: INTRODUCTION

1.1 Introduction and Background Information

Fluvial environments are greatly affected by erosion, transportation and deposition of sediments since these processes can change river morphology, conveyance, and habitat. Erosion due to agricultural land development and mining activities may introduce large amounts of sediment into streams and rivers due to overland runoff after storm events. Sediment transport in rivers is associated with several water quality and engineering issues including chemical transport of contaminants, accumulation of contaminants in organism in the bottom of the food chain, and habitat disturbance by silting or erosion of fish spawning beds (Ongley, 1996). Sediment deposition can lead to navigation problems, reduced flood carrying capacity, and siltation in reservoirs.

Sediment is transported by, suspended in, or deposited by water or air, or accumulated in beds by other natural agents. Particles range in size from large boulders to colloidal-sized fragments and vary in shape from rounded to angular. Sediment enters fluvial environments from land surface erosion, or from channel bed and bank erosion. When eroded, hydraulic forces are exerted upon the sediment particles. The resistance to transport by suspension due to the hydraulic forces is related to the particle's fall velocity, which is correlated to particle size, shape, and density, and fluid viscosity. Sediment can be transported as suspended-sediment load and bed load. Suspended-sediment load is comprised of finer sediment particles that are brought into suspension when turbulent velocity fluctuations are sufficient to maintain the particles within the fluid without frequent bed contact (Julien, 2010). Suspended-sediment load is therefore primarily comprised of sand, silt and clay particles.

Sediment monitoring in fluvial environments is critical because of the need to understand sediment supply, transport, and deposition to make proper management decisions. Sediment can be monitored by measuring suspended-sediment concentration (SSC) in rivers and streams. The Federal Interagency Sedimentation Project (FISP) was created to unify and standardize the research and development activities of Federal agencies involved in fluvial sediment studies. The FISP has conducted several research projects on indirect methods (i.e., surrogate methods) of measuring sediment characteristics to enhance resolution and accuracy.

Suspended sediment can be directly sampled with either depth-integrating or point samplers. A depth-integrating sampler is designed to isokinetically and continuously accumulate a representative sample while transiting a vertical water column at a uniform rate. A point sampler collects samples at a stationary point location. It uses a remotely operated valve to start and stop sample collection (Davis, 2005). Water samples undergo laboratory analyses to determine both SSC and particle-size distribution (PSD).

Suspended-sediment concentration is described most frequently as the ratio of sediment particle mass to water-sediment mixture volume as follows:

$$SSC_m = \frac{M_s}{V_T}$$
 Eq. 1

where the units of SSC_m are in milligrams per liter (mg/L), M_s is the mass of sediment (mg), and V_T is the total volume of the water-sediment mixture (L). Other methods of quantifying SSC include the volumetric sediment concentration (SSC_v) and the concentration in parts per million (SSC_{ppm}) as follows:

$$SSC_v = \frac{V_S}{V_T}$$
 Eq. 2

$$SSC_{ppm} = 10^6 * \left(\frac{SSC_v G}{1 + (G - 1)SSC_v}\right)$$
 Eq. 3

where, V_s is the volume of sediment (mL), and V_T is the total volume of water-sediment mixture (L), and *G* is the sediment specific gravity.

Several surrogate methods have been developed to measure SSC in fluvial environments including laser-diffraction instruments, acoustic instruments, and remote sensing. SSC can be measured using laser diffraction instruments, such as the Laser In Situ Scattering and Transmissometry (LISST), which are submerged in water to directly measure laser diffraction and therefore indirectly measure SSC. Acoustic instruments such as the acoustic Doppler current profiler (ADCP) can measure acoustic backscatter in water, which has been correlated to SSC and can therefore be converted to provide a surrogate measurement of SSC. Remote sensing techniques of measuring SSC use surface reflectance measured by multispectral sensors in satellites or cameras. Surface reflectance can be correlated to SSC to provide an indirect measurement of SSC by creating surface reflectance-SSC models.

1.2 Research Objectives

Methods for estimating SSC in fluvial systems have evolved over several decades from direct water-sample measurements to surrogate measurements including laser diffraction instruments, acoustic methods, and remote sensing. Suspended-sediment concentration monitoring with surrogate methods are rising in importance due to the generally reduction in SSC monitoring (e.g., cessation of continuous SSC monitoring on the Mississippi River). The remote sensing method of predicating SSC uses measurements of reflectance from the water surface. However, SSC is not distributed uniformly within a channel cross section. Rouse (1937) developed an equation to numerically represent vertical distributions of SSC. Vertical profiles created from the Rouse equation show increasing SSC from the water surface to the channel bottom. Suspended-sediment concentration predicted by surface reflectance may only be

detecting SSC at the water surface and consequently the estimate may not adequately represent the concentration throughout the entire water column. The main objectives of this study were to:

- evaluate the performance of laser diffraction and remote sensing surrogate methods for measuring SSC;
- investigate cross-sectional distributions of suspended sediment in the Mississippi River;
- compare theoretical Rouse SSC vertical distributions to experimental vertical SSC distributions to observe transferability of Rouse profiles onto large rivers.

These objectives were met by collecting and analyzing SSC samples at two USGS gaging stations on the Mississippi River: St. Louis, MO (07010000) and Chester, IL (07020500).

CHAPTER 2: LITERATURE REVIEW

2.1 Mississippi River SSC Monitoring

The Mississippi River basin, the largest watershed in the northern hemisphere, has a total length of 2,350 miles with its source in Minnesota at Lake Itasca and its outlet at the Gulf of Mexico. The Lower Mississippi River runs from Cairo, IL to the Gulf of Mexico. The Mississippi River plays an important role as a source of drinking water to millions of people and serves as a navigation channel for transport of goods. The Mississippi River system is crucial to national trade in the United States, as it transported 317 million tons of commodities in 2017 from the Midwest to the Gulf of Mexico (USACE, 2017).

The USGS has been delegated the responsibility of water data collection in the United States by the U.S. Department of the Interior and is the primary entity collecting suspendedsediment data at gaged locations across small streams and large rivers throughout the United States. (Lee and Glysson, 2013). The USGS has a sediment data portal which provides access to discrete and/or daily suspended-sediment data from gage sites. Daily suspended-sediment data are daily mean estimates of SSC computed at sites where SSC samples are collected approximately hourly or daily. Eight gaging stations along the main stem of the Mississippi River have historically collected daily suspended-sediment data (Table 1). All of the USGS gage stations are located on the Upper Mississippi River and have ceased collection of daily suspended-sediment data.



Figure 1: USGS data collection stations for SSC on the Mississippi River.

 Table 1: Mississippi River SSC USGS data collection periods.

			Period of Daily Suspended-Sediment Data	
			Collection	
	Station		Begin Date	End Date
River	(Location, State)	Station ID	(mm/dd/yyyy)	(mm/dd/yyyy)
Mississippi	Brooklyn Park, MN	05288500	8/20/1975	9/29/1996
Mississippi	Winona, MN	05378500	12/13/1974	9/29/1988
Mississippi	McGregor, IA	05389500	7/1/1975	9/29/2004
Mississippi	Bellevue, IA	05416100	10/1/1994	9/29/1997
Mississippi	Clinton, IA	05420500	10/1/1994	9/29/1997
Mississippi	St. Louis, MO	07010000	9/30/1980	9/30/2017
Mississippi	Chester, IL	07020500	10/1/1982	9/30/2017
Mississippi	Thebes, IL	07022000	10/1/1982	9/30/2017

Heimann et al. (2011) investigated suspended-sediment loads and concentrations in the Mississippi River Basin for the period of 1950 to 2011. The study found that during the period of analysis, suspended-sediment loads (SSLs) and flow-weighted concentrations had a downward trend. The Mississippi River major subbasins, Upper Mississippi, Lower Mississippi, Missouri, Arkansas, and Ohio River basins, were all affected by channel modification, navigation structures, and main-stem or tributary impoundments. The Missouri River drains 43% of the total Mississippi River basin area but only contributes 12% of the total water (Meade and Moody, 2010). The Missouri River is the biggest contributor of SSC to the Mississippi River, however contributions have been reduced due to impoundments, bank-stabilization, and soil conservation practices. Sediment discharge declined the most rapidly between the 1950s and the mid-1960s (Meade and Moody, 2010), with the largest decline coinciding with closure of the Fort Randal Dam on the Missouri River in 1952. After the mid-1960s, the decline in SSC continued but less rapidly. In the most recent period from 1998 – 2009, a majority of the Mississippi River basin gage stations also showed downward temporal changes in river SSC and flows (Heimann et al., 2011). The reductions in Mississippi River SSC have negative impacts such as main channel bed degradation. Decrease in SSC along with the reduction in overbank flow are also considered to be main causes of coastal wetland loss in the Gulf of Mexico (Kesel, 1989). Continued monitoring of SSC in the Mississippi River basin is necessary for making important engineering and management decisions as well as performing relevant research.

2.2 Laser-Diffraction

2.1.1 LISST Instrumentation

Laser-diffraction based particle size analyzers are currently being used to measure particle sizes and concentrations in fluvial, and marine and coastal environments. Sequoia Scientific, Inc. introduced the first submersible commercial instruments for particle sizing based

on laser diffraction. Sequoia Scientific's LISST systems are self-contained, compact and programmable. The LISST-200X measures PSD and concentration, as well as the small-angle optical volume scattering function. Several versions of the LISST instrument have been used to measure SSC and PSD in fluvial environments (Melis et al., 2003, Agrawal et al., 2012; Czuba et al., 2015; Dos Santos et al., 2017).

Melis et. al. (2003) used the LISST-100X Type B instrument, which measures particles in the size range of 1.25 to 250 microns, to test its applicability for continuous monitoring of suspended sediment in Colorado River in Arizona. The LISST-100X Type B (LISST-100B) volumetric data were converted to mass data with a gravimetrically determined density conversion. The LISST data that were collected over a 24-hour period at a fixed-depth close to the bank compared well with point measurements that were collected nearby with D-77 isokinetic bag samplers. The LISST-100B was also able to detect the expected variation of sand concentration with increasing flow rate. Melis et al. (2003) concluded that the LISST-100B was able to support continuous monitoring on the Colorado River, with weekly maintenance of optics.

Agrawal et. al. (2012) studied PSD and vertical SSC distributions in the Colowitz River in Washington State using a LISST-SL instrument. The measured volumetric concentration was not converted for this study. Results from this study showed that measured concentration, at a fixed depth, varied by a factor of two or higher. The study found that vertical gradients in SSC had the steepest gradient in course sands. The gradients of vertical SSC profiles of different particle sizes were also found to follow theoretical SSC profiles detailed in Rouse (1937). The study concluded that the LISST-SL instrument was able to give detailed PSD and SSC data within a water column.

Czuba et. al. (2015) compared SSC and PSD measured by the LISST-SL instrument and FISP isokinetic physical samplers in the Illinois and Washington river basins. The study found that when mass SSC was estimated by converting the LISST volumetric SSC with a measured sediment density of 2.67 mg/L, errors averaging over 100% occurred. A computed best-fit effective density for the whole dataset was found to be 1.24 g/mL, however Czuba et al. (2015) noted that this computed effective density was physically unrealistic to obtain. The study found that 30% of the dataset computed effective densities below one g/mL. Low effective densities would indicate floating material, which were not observed in the study. Therefore, the computed effective density, which was used to convert volumetric SSC to mass SSC, served as a conversion factor. From the observations, the study suggested that accurate SSC measurements from the LISST-SL in fluvial environments require applying an effective density less than the density of sediment particles. Physical SSC samples could be taken to obtain a site-specific effective density.

Dos Santos et. al. (2018) used a LISST-100X to evaluate the laser-diffraction method of measuring SSC in the Mogi-Guaçu reservoir in São Paulo, Brazil. Physical samples were collected with a Van Dorn Bottle to obtain SSC for calibration of the LISST-100X volumetric SSC data. This study used linear regression between the volumetric SSC and physical-sample SSC to obtain the effective density value. Three methods for the linear regressions were studied: regression by date of sampling, regression by sector of reservoir, and regression considering all data points. Regression by sector of reservoir resulted in the highest coefficients of determination and was therefore adopted to convert all volumetric SSC throughout the reservoir. The resulting regression by reservoir segment inferred that the SSC had variable characteristic behavior in different segments of the reservoir. The case study proved that the method was suitable for

obtaining a higher volume of data than conventional physical sampling techniques by significantly reducing data collection time in the field and time spent processing samples in a lab.

2.1.2 LISST-200X

The laser diffraction principle for the LISST-200X employs four main parts; the laser, the receiving lens, the detector array and the photodiode (Sequoia Scientific, 2018). The laser is collimated and the particles in the water passing through the optical window scatter the laser light. The laser light arrives, through a daylight rejection filter, at the focal plane of a receiving lens at the same angle from the lens axis. The distance from the lens axis in the lens focal plane corresponds to the scattering angle. The detector array consists of a series of silicon rings spanning 60-degree arcs and each ring covers a small range of scattering angles. The LISST-200X measures scattering at 36 angles, therefore it obtains 36 size classes of particles. Each ring in the detector has an inner and outer radius, that increases at a fixed ratio following a logarithmic trend. The change in ring areas is arranged to reduce the dynamic range of outputs of the 36 rings. Light intensity, as a function of angle, carries over several orders of magnitude and the log-spacing of rings reduces the photo-current out of the ring array to about three orders of magnitude. These photocurrents are amplified, passed through an analog to digital converter, and recorded as raw data on the LISST data logger. They become the 36 bits of primary data, which are solved like algebraic equations to obtain the PSD.

A photodiode located behind the detector array measures the power in the laser light beam that passes through a hole in the center of the detector array. This measurement is known as the optical transmission, which is the proportion of light transmitted through a turbid medium. The light is attenuated due to absorption in the medium or it may be scattered out of the beam. The measurement of optical transmission represents the amount of light that is removed which is

equal to the light falling on the cross-sectional area of the particle. Optical transmission is therefore a measurement of particle area concentration. For the LISST-200X, the optical transmission is essential to de-attenuate the signal since it is a measurement of how much the signal has weakened due to attenuation. Once the signal is de-attenuated and background (the light on the rings with filtered water) is subtracted, an inversion produces the 36-element PSD by converting multi-angle scattering measurements to the PSD. The volumetric SSC measured by the LISST-200X is defined as the total volume concentration in parts per million and is the sum of the volume concentration measured in each of the 36 particle size bins.

2.2 Remote Sensing

Remote sensing has been used within the past few years as a tool to measure SSC in large rivers such as the Mississippi River (Pereira, 2017) and the Amazon River (Mertes, 1993). Pereira et al. (2017) developed an empirical relationship between surface reflectance in the green, blue, red and near-infrared (NIR) bands from Landsat satellites and SSC for the Middle Mississippi River (MMR). The study developed three empirical SSC equations using data from the following satellites: Landsat 4-5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS). The equations were created for further SSC studies along the Middle-Mississippi River and its tributaries, however, during model application several SSC values were predicted as negative values due to the linear form of the equations. Revised Landsat surface reflectance – SSC regression equations were created and used in this study.

2.2.1 Revised Reflectance SSC Models

Landsat satellites collect data with moderate temporal and spatial resolution and provide that data to the public to facilitate research on the world's natural resources. The Landsat

program is a joint effort between the USGS and the National Aeronautics and Space Administration (NASA). Landsat satellite data can be accessed for free through Landsat Data Access Portals. Landsat Level-2 science data products can be correlated to surface reflectance to create surface reflectance-SSC regression models. Landsat Tier 1 band surface reflectance for blue, red, green and NIR bands were used as independent variables in the regression analysis. Surface reflectance values were taken from sampling areas at four USGS gage station locations, two on the Mississippi River and two on the Missouri River. Rectangular sampling areas were delineated on the Mississippi river at Thebes, IL and Chester, IL and on the Missouri River at Hermann, MO and St. Charles, MO. Subsequently, images from the dataset were removed if any pixels within the sampling area were not classified as water with low cloud confidence by the Landsat pixel quality product. For the remaining images, surface reflectance was extracted from pixels within each rectangular100 meter (W) by 330 meter (L) sampling area for each band (green, blue, red, and NIR). The mean surface reflectance and standard deviation for the rectangular sampling area was then calculated for each band.

Subsequently, the following chronological filters were used on each Landsat image to generate the final dataset: blue band mean surface reflectance filter (to remove images with cirrus cloud cover) and surface reflectance standard deviation filter (to remove images with vessel traffic in the sampling area). Details of the development of these filter methods are provided in Pereira et al. (2017). A power-regression equation was used with the least-squares fitting method to determine the best final form of the surface reflectance-SSC models. The final surface reflectance-SSC equations are shown in Table 2.

Landsat Sensor	Reflectance-SSC Empirical Relationship
8 OLI/TIRS	$SSC(mgl^{-1}) = 159.9 \left(\frac{b2}{b5}\right)^{-0.1337} \left(\frac{b3}{b5}\right)^{-5.182} \left(\frac{b4}{b5}\right)^{3.663} + 87.67$
7 ETM+	$SSC(mgl^{-1}) = 111.3 \left(\frac{b1}{b4}\right)^{-0.2684} \left(\frac{b2}{b4}\right)^{-6.033} \left(\frac{b3}{b4}\right)^{5.031} + 63.84$
4-5 TM	$SSC(mgl^{-1}) = 74.80 \left(\frac{b1}{b4}\right)^{-1.387} \left(\frac{b2}{b4}\right)^{-4.639} \left(\frac{b3}{b4}\right)^{4.227} + 80.68$

Table 2: Landsat surface reflectance-SSC models.

Note. For Landsat 8 OLI/TIRS, b2, b3, b4, and b5 are blue, green, red, and NIR band surface reflectance, respectively; and for Landsat 7 ETM+ and 4-5 TM b1, b2, b3, and b4 are blue, green, red and NIR band surface reflectance, respectively.

2.3 Suspended-Sediment Distributions

Rouse (1937) studied vertical distributions of SSC in fluvial systems and found that for a given state of flow, the relative vertical distribution of the different particle sizes is based upon their settling velocities as shown in Figure 2 The Rouse (1937) formula for vertical distribution of SSC is shown as follows:

$$\frac{c}{c_a} = \left[\left(\frac{h-z}{z} \right) \left(\frac{a}{h-a} \right) \right]^P$$
 Eq. 4

$$P = \frac{\omega}{\kappa u_*} \qquad \qquad \text{Eq. 5}$$

where *C* is SSC at *z* (mg/L); *z* is elevation above the bed (ft); *C*_a represents the reference SSC at a (mg/L); *a* is reference elevation above the bed elevation (ft); *h* is flow depth (ft); ω is the settling velocity (ft/s); κ is Von Karman's constant; *u*_{*} is shear velocity (ft/s); and *P* is the Rouse number. For this study, the following relative depth variable, *z*', was defined:

$$z' = \left(\frac{h-z}{z}\right) \left(\frac{a}{h-a}\right)$$
 Eq. 6

As shown in Figure 2, the sediment distribution curves developed from the Rouse equation show increasing SSC from the water surface to the channel bottom.



Figure 2: Rouse profiles from various Rouse numbers.

Rouse theoretical SSC distributions and experimental SSC distributions in natural streams were investigated by Anderson (1942). The study collected SSC data on a straight reach of the Enoree River located in South Carolina, where the channel width was about 50 feet. The collected SSC data were divided into five grade sizes from 0.074 mm to 0.701 mm. These data were plotted to determine an experimental Rouse number for each grade size. The theoretical value of the Rouse number was also calculated using Eq. 5 and the fall velocity of the sphere whose diameter was equal to the mean of the grade size considered. The study found that theoretical Rouse numbers were approximately two times larger than the experimentally obtained values, and that the difference increased with increasing grain size. The principal

conclusion was that SSC was more uniformly distributed than predicted by theory but the shape of the experimental SSC vertical profiles matched well with the theoretical SSC vertical profiles.

Akalin (2002) analyzed the effect of water temperature on particle fall velocity. The study also investigated the effect of water temperature and particle size on the Rouse Number. The study found that effect of water temperature is different for different particle sizes. The fall velocities of particle sizes greater or less than sand particles stay the same regardless of water temperature. However, an increase in fall velocity was observed for sand particles with median particle diameters from 0.125 mm to 1 mm. The main reason for the change was because the increase in water temperature causes a decrease in the kinematic viscosity of water. The study showed that measured Rouse numbers increased with increasing water temperature and particle size, which confirmed that the expression for the Rouse number is accurate with the fall velocity being a dominate factor. Akalin (2002) compared experimental and theoretical Rouse numbers for different particle size ranges and found a difference exists between experimental and theoretical Rouse numbers and the difference increased with increasing sand size, but the very fine sand sizes.

CHAPTER 3: STUDY LOCATION AND DATA COLLECTION

3.1 Study Location

The location for this study was the MMR. Two data collection sites were chosen along the MMR as shown in Figure 3. These collection sites were located at USGS gaging stations at Chester, IL (07010000) and St. Louis, MO (07020500). Field data collection dates coincided with Landsat 8 satellite collection dates, so that LISST-200X SSC data and SSC determined from the physical water samples could be compared to SSC estimated from the previously created reflectance-SSC models. The field data collection dates were also selected to occur during the summer months for a lesser likelihood of cloud coverage since Landsat surface reflectance data are affected by clouds. The two field collection dates were on June 14th, 2018 and August 1st, 2018.



Figure 3: Data collection sites on the Middle-Mississippi River.

3.2 Data Samplers

Field data were collected with a LISST-200X instrument, a US D-96 depth-integrated suspended-sediment sampler, and a US P-6 point integrating suspended-sediment sampler. The LISST-200X instrument configuration was done prior to entering the field. The clean water background measurement was acquired in the Water Resources Lab at Saint Louis University on June 4th, 2018 and was used on both collection dates. The LISST-200X operating mode was set to a fixed sampling rate at one second intervals (one Hz). The external mechanical switch was set as both the start and stop condition for the instrument. The LISST-200X deployment guidelines require the instrument to be deployed perpendicular to the water current with water flowing

unobstructed through the optical end of the instrument. Sequoia Scientific provided Saint Louis University a 3-D printed S-shaped scoop attachment for the LISST-200X, shown in Figure 4. The S-shaped scoop was inserted into the optics endcap (Figure 5) so that water would flow into the optical window while the instrument is oriented parallel to the water current.



Figure 4: Close-up view of LISST-200X (a) optics endcap and (b) optics endcap with S-shaped scoop inserted.



Figure 5: LISST-200X instrument (a) without S-shaped scoop and (b) with S-shaped scoop installed.

The USGS facilitated data collection at both sites by allowing the researchers to join their sampling activities. The USGS sampling was conducted on a field boat equipped with a singlearm hydraulic crane lift attached to the boat's bow. They also provided the US D-96 (Figure 6a) and US P-6 (Figure 6b) sediment samplers. During sampling, sediment samplers were attached, one at a time, to the crane's cable and lowered into the water at a rate of 0.4 ft/s.



Figure 6: FISP suspended-sediment samplers (a) US D-96 and (b) US P-6. The LISST-200X has an unsubmerged weight of 11.8 pounds and a submerged weight of 3.8 pounds. The weight of the LISST-200X alone is insufficient to resist the instrument from becoming misaligned with the water current. The US D-96 sediment sampler has a sufficient unsubmerged weight (132 pounds) and streamlined shape to keep itself aligned with the river's current. For the Chester site, the LISST-200X was deployed by attaching it to the top of the US D-96 sampler. The LISST-200X was lowered into the water at a rate of 0.4 ft/s. For the St. Louis site, the LISST-200X was attached to a 40-lb lead torpedo weight, as shown in Figure 7.



Figure 7: LISST-200X attached to 40-lb Torpedo Weight and crane system.

3.3 Field Data Collection

Data were collected using the LISST-200X at the two Mississippi River cross-sections (i.e., Chester and St. Louis). Physical water samples were taken concurrently with the LISST-200X using the US D-96 depth integrating suspended-sediment sampler and the US P-6 point sampler. LISST-200X and US D-96 depth-integrated samples were taken vertically along the Chester, IL cross section and the St. Louis, MO cross section. At the Chester site, five depth-integrated samples were taken at the 10%-, 30%-, 50%-, 70%-, and 90%-discharge width points, shown in Figure 8. The 10%-discharge width point was located at the Illinois side of the Mississippi River and the 90%-discharge width point was on the Missouri side. Seven point samples were collected with the US P-6 sampler at the Chester 50%-discharge width location at five-foot depth increments from five to thirty five feet (5, 10, 15, 20, 25, 30, and 35 ft). The data collection points for Chester are detailed in Figure 9.



Figure 8: Data collection points at the Chester, IL site.



Figure 9: Data collection schematic for the Chester, IL site.

At the St. Louis site, ten depth-integrated samples were taken at 5%-, 15%-, 25%-, 35%-, 45%-, 55%-, 65%-, 75%-, 85%-, and 95%-discharge width locations, as shown in Figure 10. The 5%-discharge width location was on the Illinois Side of the Mississippi River and the 95%-discharge width location was on the Missouri side. Twelve points samples were taken at the St. Louis 25%- and 75%-discharge width locations; six samples at 25% and six samples at 75%. The St. Louis point samples were collected at five-foot depth increments from five feet to thirty feet (5, 10, 15, 20, 25, and 30 ft) at the 25%-discharge width location. For the 75%-discharge width location, six samples were taken from five feet to thirty-five feet, excluding the twenty-foot point (5, 10, 15, 25, 30 and 35 ft). Data collection locations are detailed in Figure 11 for the St. Louis site.



Figure 10: Data collection points at the St. Louis, MO site.



Figure 11: Cross-sectional data collection schematic for St. Louis, MO. The LISST-200X 'point' samples were taken by lowering and stopping the LISST-200X at fivefoot increments. The LISST-200X was kept stationary at each five-foot increment for a one-
minute period. At least 60 measurements were made during each one-minute period because the sampling rate for the LISST-200X collection was set at one Hz. The average of the measurements recorded over the one-minute period was used to represent the LISST-200X 'point' samples.

CHAPTER 4: METHODOLOGY

4.1 SSC from Physical Water Samples

Physical water samples collected with the US D-96 suspended-sediment sampler and the US P-6 Sampler were processed to determine SSC and PSD. The June 14th water samplers were processed at the USGS Kansas City Program Office. Suspended-sediment concentration was processed according to the Guy (1969) (Techniques of Water-resources Investigations Book 5 Chapter 1 (TWRI_5-C1)) procedure for determining SSC. PSD analysis was done according to the TWRI_5-C1: procedure for the visual accumulation tube-pipet method. PSDs were only determined for the following particle sizes: 1.00, 0.500, 0.25, 0.125, and 0.062 mm.

The August 1st physical water point samples were processed at Saint Louis University Environmental Engineering Lab (Figure 12). Suspended-sediment concentration was determined by the ASTM Standard Test Methods for Determining Sediment Concentration in Water Samplers (ASTM D3977-97) Test Method A - Evaporation procedures (ASTM, 2013), and PSDs were determined according to TWRI_5-C1 Dry Sieve analysis procedures. Depth-integrated samples taken on August 1st were processed by the USGS Kansas City Program Office using the same procedures for determining SSC as the June 14th data.



Figure 12: August 1st, 2018 St. Louis samples being dried for SSC analysis in the Saint Louis University Environmental Engineering Lab.

4.2 LISST-200X Data

The LISST-200X volumetric SSC data (ppm) were converted to mass SSC (mg/L) by correlating LISST-200X depth-integrated and 'point' data to US D-96 suspended-sediment sample data and US P-6 point sample data, respectively. Best-fit power regressions were found using the least-squares method for the entire dataset and for each site individually.

The following analyses was conducted with the converted LISST-200X data:

development of vertical SSC profiles from the one-minute time-averaged 'point' values for the 50%-discharge width location for Chester, and the 25%- and 75%- discharge width locations for St. Louis;

- comparison of ascending and descending vertical profiles for all data collection locations;
- comparison of SSC from the one-minute time-averaged LISST-200X 'point' samples with the US P-6 point sample data;
- 4. cross-sectional SSC distributions from interpolated LISST-200X vertical profiles; and
- comparison of LISST-200X PSD with PSD from the US D-96 depth-integrated suspended-sediment samples.

4.3 Surface Reflectance-SSC

The Landsat 8 OLI/TIRS Collection 1 Level-1 images were obtained from USGS Earth Explorer online platform for June 14th, 2018 and August 1st, 2018. The images were processed according to the method described in Section 2.2.1 and estimated SSC values were calculated using the Landsat 8 reflectance-SSC model from Table 2. The remote sensing SSC data were compared to the direct measurements of SSC and the estimated SSC values from the LISST-200X data.

4.4 Rouse Profiles

Rouse profiles were created using theoretical and experimental Rouse numbers. Theoretical Rouse numbers were calculated separately for the Chester and St. Louis site. The theoretical Rouse number, P_t , was calculated according to following equation (Rouse, 1937):

$$P_t = \frac{\omega}{u_* \kappa}$$
 Eq. 7

where ω is the particle settling velocity (ft/s), u_* is the shear velocity (ft/s), and κ is the Von Karmen constant. Settling velocity was calculated using Stoke's equation for settling velocity in clear water as follows (Julien, 2010):

$$\omega_0 = \frac{1}{18} \frac{(G-1)g}{v} d_s^2$$
 Eq. 8

where *G* is relative density, *g* is acceleration due to gravity (ft/s^2), *v* is kinematic viscosity of water in (ft^2/s), and *d_s* is particle diameter (ft). Shear velocity was calculated with the following equation:

$$u_* = \sqrt{\frac{\gamma h S_0}{\rho}} = \sqrt{g h S_0}$$
 Eq. 9

where γ is specific weight of water (lb/ft³), *h* is flow depth (ft), *S*₀ is bed slope, and ρ is density of water (slugs/ft³). The flow was assumed to be steady and uniform, therefore the bedslope, *S*₀, was assumed to be equal to the water surface slope, *S*_w. The water surface slope was calculated for each station using gage height data to calculate water surface elevations, *WSE*, for neighboring USGS gage stations. Water surface elevation at a gage station was calculated using the following equation:

$$WSE_{gage X} = Datum of gage X + Gage X height$$
 Eq. 10

The water surface slope, S_w , was calculated with the following equation:

$$S_w = \frac{WSE_{upstream\ gage} - WSE_{downstream\ gage}}{Distance\ between\ gages}$$
Eq. 11

Experimental Rouse numbers, P_e , were found by correlating LISST-200X relative SSC data, C/C_a , to the base term, z', in Eq. 4 to find the best-fit power regression curve. Relative SSC data were obtained from LISST-200X SSC data, where *C* is the SSC at height *z* above the channel bottom and C_a was assumed to be the SSC at the deepest point in the vertical column.

4.5 Depth-Integrated SSC from Coupling SSC at the Water Surface with Rouse Profiles

The Rouse (1937) equation could be used in a practical application to predict total SSC in a vertical water column with a known surface SSC value obtained from remote sensing and a known Rouse number. The concentration at height 'a' above the channel bed could not be easily

attainable or measured, but Eq. 4 could be rearranged into Eq. 12 to find a value of C_a if the SSC at a certain specific depth, *i*, above the channel bed is known.

$$C_a = \frac{C_{z_i}}{\left[\left(\frac{h-z_i}{z_i}\right)\left(\frac{a}{h-a}\right)\right]^P}$$
Eq. 12

For this analysis, the SSC at the surface, C_o , was obtained from the LISST-200X SSC data point nearest to the water surface. The LISST-200X data were used for this analysis instead of the remote sensing measurements because the remote sensing regression models were design to predict the cross-sectional averaged SSC and not the SSC at the water surface. The surface SSC value, C_o , was assumed to be representative of the SSC at 95% of the total depth, h, above the bed; C_a was still assumed to be the SSC at height 'a' which is 5% of the total depth, h, above the bed. The following expression can be derived by substituting the assumed C_o and C_a elevation information into Eq. 12:

$$C_a = \frac{C_0}{0.00277^P}$$
 Eq. 13

The depth-integrated SSC, C_{TOT} , in a vertical water column could therefore be calculated as follows:

$$C_{TOT} = \frac{1}{0.90h} \int_{z=0.05h}^{z=0.95h} C_z dz$$
 Eq. 14

where C_z is the SSC at depth *z* above the bed. Substituting Eq. 4 into Eq. 14 produces the following expression for the depth-integrated SSC value:

$$C_{TOT} = \frac{1}{0.90h} \int_{z=0.05h}^{z=0.95h} \left\{ C_a \left[\left(\frac{h-z}{z} \right) \left(\frac{a}{h-a} \right) \right]^p \right\} dz$$
 Eq. 15

Further, substituting in C_a from Eq. 13 into Eq.15 and using *h* as a relative height of one, the depth-integrated SSC can be calculated using the following equation:

$$C_{TOT} = \frac{1}{0.90} \left(\frac{C_0}{0.00277^P} \right) \int_{0.05}^{0.95} \left[\left(\frac{1-z}{z} \right) (0.0526) \right]^P dz$$
 Eq. 16

Eq. 16 can be simplified to the following form:

$$C_{TOT} = \frac{C_0(18.99^P)}{0.90} \int_{0.05}^{0.95} \left(\frac{1-z}{z}\right)^P dz$$
 Eq. 17

Best-fit Rouse numbers, *P*, for predicting depth-integrated SSC were identified by evaluating Rouse numbers ranging from 0.01 to 0.2 with LISST-200X SSC data collected near the water surface. Computed depth-integrated SSC, *C*_{TOT}, was compared to the measured US D-96 depth-integrated SSC and the least-squares method was used to identify the optimal Rouse number. The analysis was conducted separately for the Chester and St. Louis sites.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 SSC from Physical Water Samples

Physical water samples from the US P-6 sediment sampler were processed in the laboratory and the results are shown in Table 3 and Table 4 for Chester and St. Louis, respectively. The detailed results from the St. Louis samples that were processing in the Saint Louis University lab are shown in Table 18 and Table 19 in Appendix A. Point samples were taken at every five-foot increment except for the 35-ft depth at the 25%-discharge width location at St. Louis because the channel was not deep enough and the 20-ft location at the 75%-discharge width location at St. Louis because of limited sampler bottles. For the Chester site, SSC values ranged from 100.0 to 180.0 mg/L; and for the St. Louis site, SSC values ranged from 80.4 to 99.9 mg/L for the 25%-discharge width location.

Depth (ft)	US P-6 SSC (mg/L)
5	100.0
10	113.0
15	104.0
20	128.0
25	122.0
30	171.0
35	180.0

Table 3: US P-6 point sediment samplers SSC values for Chester, IL.

Depth (ft)	25%-Discharge Width	75%-Discharge Width
-	US P-6 SSC (mg/L)	US P-6 SSC (mg/L)
5	94.0	153
10	81.7	155
15	99.9	131
20	98.0	n/a
25	80.4	149
30	86.7	178
35	n/a	144

Table 4: US P-6 point sediment samplers SSC values for St. Louis, MO.

n/a = not available

5.2 LISTT-200X Data

5.2.1 Converting LISST-200X Data

The LISST-200X data were converted as described in Section 4.2. The best-fit curve for the combined Chester and St. Louis dataset had a coefficient of determination of 0.524 (Figure 13). When the Chester and St. Louis data were evaluated separately the coefficients of determination increased to 0.671 and 0.572 for Chester and St. Louis, respectively (Figure 14 and Figure 15). The final best-fit power functions used were the separated station equations because they produced higher coefficients of determinations compared to the fit for the entire dataset. All LISST-200X SSC values reported in the results and discussion section were found using the conversions shown in Figure 14 and Figure 15.



Figure 13: Physical sample mass SSC – LISST-200X volume SSC regression for combined dataset (Chester, IL and St. Louis, MO).



Figure 14: Physical sample mass SSC – LISST-200X volume SSC regression for Chester, IL dataset.



Figure 15: Physical sample mass SSC – LISST-200X volume SSC regression for St. Louis, MO dataset.

5.2.2 LISST-200X SSC Vertical Profiles

Vertical SSC profiles were created from LISST-200X SSC data. The vertical SSC profiles for 50%-Q width at Chester and the 75%- and 25%-Q widths at St. Louis are shown in Figure 16 and Figure 17, respectively. They were created from data collected while the LISST-200X was descending at five-foot increments with one-minute stationary sampling. The vertical SSC profile in Figure 16 shows the one-minute, five-foot increments for the 50%-discharge width location at Chester, IL. The SSC data collected within the one-minute periods had a standard deviation ranging between 15.1 to 60 mg/L (Table 5). The average SSC collected from each of the one-minute periods showed an increase of SSC with depth below water surface.



× LISST-200X Descending at 5 ft Increments ▲ Increment Average

Figure 16: Vertical SSC distribution from one-minute period, five-foot increment LISST-200X data for the 50%-Q width at Chester, IL.

Table 5: Average SSC and standard deviation from one-minute period, five-foot incrementLISST-200X data from Chester, IL.

Depth (ft)	Average SSC (mg/L)	Standard Deviation (mg/L)
5	94.3	32.2
10	120	22.1
15	113	15.1
20	115	20.1
25	144	30.5
30	152	37.1
35	158	60.0

The vertical SSC profile in Figure 17, created from the St. Louis data, showed similar variability within the one-minute period measurements. The standard deviation at the 25%-discharge width location ranged from 3.0 - 9.4 mg/L and the standard deviation at the 75%-discharge width location ranged 5.3 to 12.1 mg/L (Table 6). These standard deviations are notably smaller than those at Chester. The average SSC from the one-minute periods showed increase in SSC with depth for both the 25%-discharge width and 75%-discharge width locations.

USGS scientists demonstrated the loss accuracy of the LISST instrument with profiles similar to those shown in Figure 16 and Figure 17, (Sequoia Scientific, 2016). Sources of noise include bias due to poor mixing and vertical gradients, and presence of particles outside the measurements range (Sequoia Scientific, 2016). Another possible source of inaccuracy could be that there were particles larger than then 500 microns that the LISST-200X was unable to measure. The Chester site (Figure 16) and the 75%-discharge width location at the St. Louis site (Figure 17) had a higher standard deviation within the one-minute collection periods than the 25%-discharge width location at the St. Louis Site.



Figure 17: Vertical profile for one-minute period, five-foot increments LISST-200X data for the 25%- and 75%-discharge widths at St. Louis, MO.

Donth	25% - Discharge Width		75% - Discharge Width	
(ft)	Average SSC (mg/L)	Standard Deviation (mg/L)	Average SSC (mg/L)	Standard Deviation (mg/L)
5	92.7	3.00	159	8.17
10	94.8	3.10	145	8.59
15	99.3	4.20	149	8.38
20	104	9.40	151	10.0
25	110	4.80	153	5.32
30	108	7.50	165	7.02
35	n/a	n/a	184	12.1
· /				

Table 6: Average SSC and standard deviation from one-minute period, five-foot incrementsLISST-200X data at St. Louis, MO.

n/a = not available.

The descending-ascending LISST-200X SSC profiles for the 50%-discharge width location at Chester, IL showed that at equivalent depths, SSC was not always identical. The LISST-200X vertical profile at the 50%-discharge width location at Chester shown in Figure 18 displayed higher concentrations at equivalent depths when the LISST-200X was descending, but the average of SSC from the one-minute periods fit mostly between the ascending and descending SSC profiles. Descending-ascending LISST-200X SSC profiles for the remaining Chester data collection locations are provided in Appendix B. They exhibited slightly closer equivalence in the descending and ascending motion, except for the 90%-discharge width location where the descending profile was higher at every point. Although the SSC would vary in some areas of profile, each descending LISST-200X SSC profile showed a general increase in SSC with depth.



Figure 18: LISST-200X vertical SSC profile at the 50%-discharge width location at Chester, IL. Vertical profiles for the St. Louis 25%- and 75%-discharge width location are shown in
Figure 19. The descending-ascending LISST-200X SSC profiles and LISST-200X one-minute averaged SSC profiles, for both the 25%- and 75%-discharge width location, were generally in agreement. Descending-ascending vertical SSC profiles for the remaining St. Louis data collections locations are provided in Appendix B. Similar to the Chester samples, each LISST-200X vertical SSC profile for the St. Louis site showed an increasing trend in SSC with depth.



Figure 19: LISST-200X vertical SSC profiles from descending-ascending deployment and average one-minute period deployment.

Temporal variability of SSC measured with the LISST-200X was shown in both the descending-ascending deployment and the one-minute period stationary depth deployment at St. Louis. LISST-200X vertical SSC profiles at St. Louis had an overall higher SSC but also higher temporal variability in SSC on the Missouri Side of the River, as shown in the ascending-descending profiles in Figure 40, Figure 41, and Figure 42 located in Appendix B. The LISST-200X vertical profiles on the Illinois side of the Mississippi River at St. Louis (Figure 43 and Figure 44 in Appendix B) had less temporal variability in SSC. Temporal variability in SSC was

shown throughout the Chester cross-section vertical SSC profiles (Figure 37, Figure 38, and Figure 39 in Appendix B) unlike the St. Louis vertical profiles that only saw significant temporal variability on the Missouri Side of the River. Less temporal variability on the Illinois side of the Mississippi river could be because the mixing zone from the confluence did not extend fully throughout the river cross-section, although the site was 20 river miles downstream of the confluence.

For the Chester site, point samples were taken at the 50%-discharge width location with the US P-6 samplers. The samples were collected at five-foot depth increments from five to thirty-five feet (5, 10, 15, 20, 25, 30, and 35 ft). The vertical SSC profiles from the physical point samples and the LISST-200X time-averaged SSC (one-minute collection periods) are shown in Figure 20. Both vertical profiles showed an increase in SSC with depth.



Figure 20: Vertical SSC profiles from physical sample and LISST-200X data at Chester, IL 50%-discharge width location.

For the St. Louis site, point samples were taken at the 25%- and 75%-discharge width locations with the US P-6 sampler. The samples were collected at five-foot depth increments from 5 ft to 30 ft (5, 10, 15, 20, 25, and 30 ft) for the 25%-discharge width location and 5 ft to 35 ft (5, 10, 15, 25, 30 and 35 ft) for the 75%-discharge width location, respectively. The physical SSC samples at the 75%-discharge width location were on average 1.7 times higher than the SSC values at the 25%-discharge width location. Vertical profiles for the physical SSC samples and the LISST-200X SSC time-averaged SSC (one-minute collection periods) are shown in Figure 21. A clear increase in SSC with depth was observed in the LISST-200X profile, while no apparent trend in SSC with depth was observed in the physical sample profile.



▲ LISST-200X Concentration at 25%-Discharge Width Location

▲ LISST-200X Concentration at 75%-Discharge Width Location

Figure 21: Vertical SSC profiles from physical sample and LISST-200X data at St. Louis, MO. The LISST-200X vertical SSC profiles from Chester and St. Louis showed increase in

SSC with depth. Vertical profiles created from US P-6 point SSC data only showed increasing SSC with depth in the Chester profile. The difference between the US P-6 point SSC and the LISST-200X 'point' SSC ranged from 3% to 43%. The St. Louis vertical profiles from US P-6 SSC were the only ones that showed no trend with depth and SSC.

Cross-sectional SSC profiles from LISST-200X data were plotted for the Chester and St. Louis sites in Figure 22 and Figure 23, respectively. The cross-section profile was created by interpolating between each vertical SSC profile (LISST-200X descending-ascending profile data). The longitudinal scale was altered by a scale factor of five to provide a clearer profile.



Figure 22: Cross-sectional SSC distribution from LISST-200X data for Chester, IL.



Figure 23: Cross-sectional SSC distribution from LISST-200X data for St. Louis, MO.

During St. Louis data collection at the 55%-, 65%-, 75%-, 85%-, and 95%-discharge width locations, the LISST-200X transmission was less than 30%. Sequoia Scientific stated that data collected at transmission values between 10% and 30% have generally decreasing data quality and suggests disregarding any data in which transmission is less than 10% because the water is too turbid. The transmission for data collection at St. Louis never dropped below 10%, therefore no data were removed. The St. Louis LISST-200X data with transmission above and below 30% did not have a significant difference in the percent error when compared to physical samples. Although decreases in data quality and accuracy was cautioned, this was not reflected in the LISST-200X data.

5.2.3 LISST-200X PSD Curves

Particle size distribution curves were created from LISST-200X data and physical sample data. Examples of the PSD curves for the 50%-discharge width location at Chester, 25%-discharge width location at St. Louis, and 75%-discharge width location at St. Louis are shown in Figure 24, Figure 25, and Figure 26, respectively. PSD curves for all other locations are provided in Appendix C. The PSD curves from the physical sample data were limited to particle sizes greater than 0.062 mm because fines particle size analysis was not performed. The median particle diameter was obtained from each LISST-200X PSD curve since all the physical sample PSD curves were missing the information. The average median particle diameter was found for each location as listed in Table 7 and Table 8 for the Chester and St. Louis sites, respectively. The average median particle diameters for the 25%-discharge width location and 75%-discharge width location were 0.035, and 0.025, respectively. The overall average median particle diameter for St. Louis was 0.030 mm.



Figure 24: PSD curves plotted from LISST-200X data and physical sample data at the 50%discharge width location at Chester, IL.



Figure 25: PSD curves plotted from LISST-200X data and physical sample data at the 75%discharge width location at St. Louis, MO.



Figure 26: PSD curves plotted from LISST-200X data and physical sample data at the 75%discharge width location at St. Louis, MO.

Table 7: Median particle diameter for suspended sediments in the Mississippi River at Chester, IL at the 50%-discharge width location.

	LISST-200X
Deptn (It)	d50 (mm)
5	0.032
10	0.035
15	0.033
20	0.033
25	0.036
30	0.036
35	0.036
Average	0.034

LISST-200X, d ₅₀ (mm)		X, d50 (mm)
Depth (ft)	25%-Discharge	75%-Discharge
	Width	Width
5	0.033	0.025
10	0.033	0.022
15	0.034	0.025
20	0.033	n/a
25	0.036	0.025
30	0.038	0.026
35	n/a	0.029
Average	0.035	0.025
Overall Average	0.030	
n/a = not available		

Table 8: Median particle diameter for suspended sediments in the Mississippi River at St. Louis, MO at the 25%- and 75%-discharge width locations.

5.3 Surface Reflectance-SSC

The collection site at Chester, IL on June 14th, shown in Figure 27, was within the Landsat Path 23 Row 34. Cirrus clouds were over the exact data collection location at the Chester site, therefore, surface reflectance-SSC for the Chester site was taken upstream from the physical data collection points. The SSC estimated from the surface reflectance was much higher than the physical sample SSC and the LISST-200X SSC, although it was only about two miles upstream of the exact site. The upstream area could have possibly still been influenced by cloud shadows, resulting in an inaccurately estimated SSC.



Figure 27: Landsat surface reflectance-SSC at Chester, IL.

The August 1st image at St. Louis, MO, shown in Figure 28, was within the Landsat Path 23 Row 33. The real color image obtained from Landsat is shown next to the surface reflectance-SSC image in Figure 28. Clear weather conditions allowed surface reflectance-SSC to be obtained for every point along the St. Louis collection site. St. Louis surface reflectance-SSC showed higher SSC on the Missouri side than the Illinois side of the Mississippi River due to the inflow of the major sediment contributor, the Missouri River, located about 20 miles upstream of the collection site. The water in the Missouri River has a visibly higher SSC than the Mississippi River at the confluence, and consequently shows a mixing zone between the two rivers. However, the extent of the mixing zone that continues downstream cannot be seen so easily in a normal 'true color' image. Landsat surface reflectance-SSC images showed the extents and overall distribution of SSC across the river cross-section at the St. Louis site.



Figure 28: Landsat surface reflectance-SSC at St. Louis, MO.

The spatial resolution allows large-scale monitoring of the SSC on a large river such as the Mississippi River. Landsat Path 23, Rows 33 – 39 covers the Mississippi River from a few river miles upstream of the Missouri River confluence, down to the Louisiana before the outlet in New Orleans. A Landsat 'path' is collected all within the same day, therefore using surface reflectance-SSC models, a large-scale, plan view, snapshot of SSC for the Mississippi River can be created for the collection day.

5.4 Comparison of Two Surrogate Methods

Depth-integrated SSC values from the samples collected using the US D-96 sediment sampler were compared with two surrogate methods, the laser diffraction method using the

LISST-200X instrument and the surface reflectance-SSC method using Landsat 8 satellite data. Depth-integrated SSC was calculated from LISST-200X SSC vertical profiles, as the average of the descending and ascending depth-integrated SSC values. Landsat surface reflectance-SSC values were taken upstream of the Chester site, because of cloud coverage, and at the exact location at St. Louis site. The SSC values from these three methods are provided in Table 9 and Figure 29 for the Chester site and in Table 10 and Figure 30 for the St. Louis site.

Table 9: SSC obtained from physical samples, laser diffraction (LISST-200X) and remote sensing (Landsat) for Chester, IL.

%-Q Width	US D-96 Depth- Integrated SSC (mg/L)	LISST-200X Depth- Integrated SSC (mg/L)	Landsat Surface Reflectance- SSC (mg/L)
10	106	123	200
30	109	125	201
50	138	133	202
70	153	155	202
90	125	133	204



Figure 29: Comparing SSC determined from physical samples to surrogate methods of determining SSC (LISST-200X and Landsat satellite) at Chester, IL.

Table 10: SSC obtained from physical samples, laser diffraction (LISST-200X) and remote sensing (Landsat) for St. Louis, MO.

%-Q Width	US D-96 Depth- Integrated SSC (mg/L)	LISST-200X Depth- Integrated SSC (mg/L)	Landsat Surface Reflectance-SSC (mg/L)
5	103	108	134
15	121	97.2	138
25	129	98.4	146
35	153	110	152
45	165	116	148
55	178	149	147
65	205	162	147
75	172	175	148
85	198	175	167
95	245	193	182



Figure 30: Comparing SSC determined from physical samples to surrogate methods of determining SSC (LISST-200X and Landsat satellite) at St. Louis, MO.

When LISST-200X and Landsat surface-reflectance SSC for both Chester and St. Louis were compared to depth-integrated SSC obtained from physical water samples, the average percent error was lower for the LISST-200X SSC (13.1%) than the Landsat surface-reflectance SSC (27.3%). When SSC was overestimated by the surrogate methods, the range of overestimation by the LISST-200X was from 2 mg/L to 17 mg/L while the range of overestimation for surface reflectance-SSC was from 17 mg/L to 94 mg/L. For the Chester site, the surface reflectance-SSC values were all overestimated because the data collection sites were not at the exact locations for accurate comparison as well as possible presence of cloud shadows. For the St. Louis site, the occurrence of surface reflectance-SSC overestimation and underestimation was almost equivalent. Underestimation of SSC occurred only on the Missouri side of the Mississippi river, at the 45% to 95%-discharge width locations. Although the

occurrence of over and underestimation were almost equivalent, the extent of underestimation was larger than the overestimation. This result could be evidence that surface reflectance-SSC models are not fully capturing the SSC within the entire water column.

The LISST-200X SSC had closest union with the actual measured SSC from physical samples out of the two surrogate methods. The LISST-200X SSC measurements were mostly underestimated at the St. Louis Site. A possible cause for underestimation of SSC by the LISST-200X is because of the instrument's measurement range. The measurements range for the LISST-200X is 0.001 mm to 0.5 mm, therefore coarse particles larger than 0.5 mm were excluded from measurement. St. Louis PSD curves (Figure 51 to Figure 60 in Appendix C), showed that particles larger than 0.5 mm were present. LISST-200X SSC measurements were more accurate at Chester than St. Louis, and only one measurement at Chester was underestimated (value underestimated by 5 mg/L). Chester PSD curves (Figure 45 to Figure 50 in Appendix C) demonstrated no presence of particles larger than 0.5 mm, therefore the LISST-200X gave a more accurate measurement of SSC for those samples than St. Louis LISST-200X SSC results.

5.5 Rouse Profile

5.5.1 Theoretical Rouse Number

The theoretical Rouse numbers were calculated using Eq. 7 for Chester and St. Louis separately. The gage heights used to calculate water surface elevations and the corresponding water surface slope on June 14th were from the Chester, IL and Thebes, IL gage stations. The gage heights used to calculate water surface elevations and the corresponding water surface slope on August 1st were from St. Louis, MO and Chester, IL gage stations. The water surface slope on both dates was found to be 0.000100. Flow depth was determined from ADCP profile data collected on June 14th and August 1st. The flow depth at Chester on June 14th was 40 feet, and the

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flow depth at St. Louis on August 1st was 32 feet. Shear velocity was found to be 0.359 ft/s and 0.335 ft/s at Chester and St. Louis, respectively. Settling velocity was calculated using the median particle diameter, d₅₀, as the particle diameter, d_s. The median particle diameters were 0.034 mm for Chester and 0.030 mm for St. Louis, respectively (Table 7 and Table 8). The settling velocity was calculated to be 0.00394 ft/s for the Chester, IL dataset. Using the calculated settling velocity, the corresponding theoretical calculated Rouse number for Chester was 0.0285. The settling velocity was calculated to be 0.00328 ft/s for St. Louis. The corresponding theoretical Rouse number for St. Louis was 0.0238. A complete summary of the data used for calculating the theoretical Rouse numbers is shown in Table 11 and Table 12 for Chester and St. Louis, respectively. The calculated theoretical Rouse numbers were almost equal for Chester and St. Louis.

D ₅₀ (mm)	0.034
Water Temperature (°C)	28
Kinematic Viscosity at 28°C, υ (ft²/s)	8.99E-06
Relative Density of Sediment, G	2.65
Acceleration Due to Gravity, g (ft/s ²)	32.2
Fall Velocity, ω [Eq. 8] (ft/s)	0.00394
Slope, Sw [Eq. 11]	0.000100
Flow Depth, h (ft)	40
Shear Velocity, u* [Eq. 9] (ft/s)	0.359
Von Karmen's constant, ĸ	0.4
Theoretical Rouse number, Pt [Eq. 7]	0.0285

Table 11: Summary of data for the theoretical Rouse number calculation for Chester.

D ₅₀ (mm)	0.030
Water Temperature (°C)	25.5
Kinematic Viscosity at 25.5°C, υ (ft ² /s)	9.49E-06
Relative Density of Sediment, G	2.65
Acceleration Due to Gravity, g (ft/s ²)	32.2
Fall Velocity, ω [Eq. 8] (ft/s)	0.00328
Slope, S _w [Eq. 11]	0.000100
Flow Depth, h (ft)	37
Shear Velocity, u* [Eq. 9] (ft/s)	0.335
Von Karmen's constant, κ	0.4
Theoretical Rouse number, Pt [Eq. 7]	0.0238

Table 12: Summary of data for the theoretical Rouse number calculation for St. Louis.

5.5.2 Experimental Rouse Number

Best-fit power regression curves were developed, using the least-squares method, to find the experimental Rouse numbers, P_e , for each LISST-200X ascending-descending vertical SSC dataset. The best-fit power regression represented the experimental Rouse number for an individual ascending-descending vertical SSC dataset. For example, the experimental Rouse number for the 50%-discharge width location at Chester, shown in Figure 31, was found to be 0.0727. The remaining best-fit power regression curves for the Chester and St. Louis site are provided in Appendix D. The average experimental Rouse numbers for each discharge-width location at Chester and St. Louis are shown in Table 13 and Table 14, respectively. The crosssectional averaged experimental Rouse numbers were found to be 0.105 and 0.0255 for Chester and St. Louis respectively.



Figure 31: Best-fit power regression curve for LISST-200X SSC data from the 50%-discharge width location at Chester, IL.

%-Discharge Width	Rouse Number, Pe
10%	0.214
30%	0.223
50%	0.0971
70%	0.127
90%	0.0629
Average	0.145

Table 13: Experimental Rouse numbers found for Chester, IL data.

%-Discharge Width	Rouse Number, Pe
5%	0.0175
15%	0.0174
25%	0.0176
35%	0.0207
45%	0.0240
55%	0.0417
65%	0.0275
75%	0.0345
85%	0.0374
95%	0.0142
Average	0.0253

Table 14: Experimental Rouse numbers for St. Louis, MO data.

5.5.3 Rouse Profiles

The predicted Rouse profiles were plotted using the averaged experimental Rouse number for each site, the location-specific experimental Rouse number, and the theoretical Rouse number. The Rouse profiles for the 50%-discharge width location at the Chester site are shown in Figure 32. The Rouse profiles predicted from the average experimental Rouse number ($P_{e,avg} =$ 0.145) fit well with the vertical SSC profiles for both physical sample and LISST-200X SSC points. The location-specific experimental Rouse number ($P_{e, 50\%-Q \text{ width}} = 0.0971$) fit the LISST-200X SSC did performed better at the bottom of the profile than did the profile from the average experimental Rouse number ($P_{e,avg} = 0.145$). The predicted Rouse profiles from the theoretical Rouse number ($P_t = 0.0285$) did not fit the points from physical sample or LISST-200X data as closely as the average location-specific experimental Rouse numbers.



Figure 32: Rouse profiles from theoretical and experimental Rouse numbers for the 50%discharge width location at Chester, IL.

Predicted Rouse profiles for the St. Louis 25%-discharge width and 75%-discharge width location are shown in Figure 33 and Figure 34, respectively. Both profiles did not represent the physical sample profile or the LISST-200X profile well. For the 25%-discharge width location, the predicted Rouse profiles from the average experimental Rouse number ($P_{e,avg} = 0.0253$) and from the theoretical Rouse number ($P_t = 0.0238$) were almost identical while the profile from the location-specific Rouse number ($P_{e,25\%-Q}$ width = 0.0176) estimated a slightly steeper SSC profile. The Rouse profiles created from experimentally-derived Rouse numbers fit the actual vertical profile for Chester and the 25%-discharge width location at St. Louis best. For the 75%discharge width at the St. Louis site (Figure 34), the predicted Rouse profiles from the average
experimental, location-specific experimental and theoretical Rouse numbers all overestimated the SSC profile. The location-specific experimental Rouse number ($P_{e,75\%-Q width} = 0.0345$) had the least steep profile, however the profile was still consistent with the LISST-200X and physical samples.



Figure 33: Rouse profiles from theoretical and experimental Rouse numbers for St. Louis, MO at the 25%-discharge width location.



Figure 34: Rouse profiles from theoretical and experimental Rouse numbers for St. Louis, MO at the 75%-discharge width location.

All of the theoretically-calculated Rouse numbers resulted in steep Rouse profiles. The theoretically calculated Rouse number is directly proportional to particle fall velocity and therefore the particle diameter and specific gravity. In this study, the equation for particle fall velocity used the median particle diameter obtained from LISST-200X PSD curves and assumed the commonly used sediment specific gravity of 2.65. Median particle diameters from the samples ranged were between 0.022 mm and 0.038 mm, but as mentioned in Section 5.2.3, the range of particle size measurement may not be representative of the actual conditions due to the measurement range. The limited measurement range could have skewed the result for the median

particle diameter, which consequently would result in a different fall velocity and therefore Rouse number.

Vertical SSC distributions of finer particles were somewhat uniform resulting in steep SSC profiles. Although the majority of measured SSC was within the silt-clay category $(d_s < 0.063 \text{ mm})$, the concentration of coarser particles is still important for predicting a total SSC. Therefore, theoretically calculated Rouse numbers based on the median particle diameter may be the reason why the point samples did not fit within the profile lines.

5.6 Depth-Integrated SSC from Coupling SSC at the Water Surface with Rouse Profiles

As detailed in Section 4.5, best-fit Rouse numbers were determined by coupling the SSC near the water surface with the theoretical Rouse profile equation (Eq. 17). For the Chester site, the Rouse number that resulted in the highest coefficient of correlation with the US D-96 SSC for Chester was 0.0270 (Figure 35). For the St. Louis site, the Rouse number with the highest coefficient of correlation with the US D-96 SSC was 0.110 (Figure 36). The best-fit Rouse number (P = 0.0270) incorporated with Eq. 17 predicted a depth-integrated SSC that better matched the US D-96 sampler (Table 15). The best-fit Rouse number incorporated with Eq. 17 predicted a depth-integrated SSC that better matched the US D-96 sampler (Table 15). The best-fit Rouse number incorporated with Eq. 17 predicted a depth-integrated SSC that better matched the US D-96 sampler, shown in Table 15 and Table 16 for Chester and St. Louis, respectively. The majority of the percent errors, for the Chester dataset, between LISST-200X surface SSC and US D-96 SSC (Table 15). The St. Louis dataset had far lower percent errors between predicted depth-integrated SSC and US D-96 SSC (Table 15).

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Table 15: Predicted depth-integrated SSC from LISST-200X data and best-fit Rouse number, P = 0.027, for Chester, IL.

%- Discharge Width	LISST-200X Surface SSC, Co (mg/L)	Predicted Depth- integrated SSC, CTOT (mg/L)	US D-96 SSC (mg/L)	Percent Error – LISST-200X Surface SSC and US D-96 SSC (%)	Percent Error – Predicted Depth- Integrated SSC and US D-96 SSC (%)
10	81.9	92.3	106	22.7	12.9
30	91.9	104	109	15.7	4.59
50	121	136	138	12.3	1.45
70	120	135	153	21.6	11.8
90	136	153	125	8.80	22.4

Table 16: Predicted depth-integrated SSC from LISST-200X data and the best-fit Rouse number, P = 0.110, for St. Louis, MO.

%- Discharge Width	LISST-200X Surface SSC, C ₀ (mg/L)	Predicted Depth- integrated SSC, CTOT (mg/L)	US D-96 SSC (mg/L)	Percent Error – LISST-200X Surface SSC and US D-96 SSC (%)	Percent Error – Predicted Depth- Integrated SSC and US D-96 SSC (%)
5	92.0	127	103	10.7	23.3
15	96.0	132	121	20.7	9.09
25	87	120	129	35.6	6.98
35	104	143	153	32.0	6.54
45	101	139	165	38.8	15.8
55	123	169	178	30.9	5.06
65	137	189	205	33.2	7.80
75	143	197	172	16.9	14.5
85	147	203	198	25.8	2.53
95	188	259	245	23.3	5.71



Figure 35: Predicted total SSC from LISST-200X data and the best-fit Rouse number, P = 0.027 for Chester, IL.



Figure 36: Predicted total SSC from LISST0-200X data and the best-fit Rouse number, P = 0.11, for St. Louis, MO.

5.7 Rouse Number Comparison

The Chester best fit Rouse number (P = 0.0270) and the theoretical Rouse number ($P_t = 0.0285$) were nearly equivalent, and both were smaller than the experimental Rouse numbers found ($P_{e,avg} = 0.145$ and $P_{e,50\%-Q}$ width = 0.0971). The best fit Rouse number for Chester (P = 0.0270) would therefore result in a steep profile similar to that made by theoretical Rouse number ($P_t = 0.0285$) shown in Figure 32. The best fit Rouse number for St. Louis was found to be 0.110 which was greater than theoretical and experimental values (Table 17). Based on the Rouse equation, a greater Rouse number could indicate a larger actual median particle diameter than measured by the LISST-200X. Although the best-fit Rouse number (P = 0.110) differed from all experimental and theoretical Rouse numbers for St. Louis the predicted total SSC matched US D-96 better than the Chester results, as mentioned in Section 5.6. With additional data, the best-fit Rouse number for the entire Middle Mississippi River could be investigated and incorporated to better predict a better depth-integrated SSC values.

Station – Location	ation –TheoreticalExperimentalExocationRouseAverage RouseNumber, PtNumber, Pe avaN		Experimental Location Specific Rouse Number, Pe %-O width	Best Fit Rouse Number, P
Chester, IL- 50%-Discharge Width Location	0.0285	0.145	0.0971	0.0270
St. Louis, MO – 25%-Discharge Width Location	0.0238	0.0253	0.0176	0.110
St. Louis, MO – 75%-Discharge Width Location	0.0238	0.0253	0.0345	0.110

Fable 17: Summary of Rouse Numbers found for Chester and St. Lor
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CHAPTER 6: SUMMARY, CONCLUSIONS AND RESEARCH RECOMMENDATIONS 6.1 Summary

Monitoring of SSC on the Mississippi River can be continued with use of new and developing surrogate methods. The LISST-200X instrument has unique cost and time saving benefits for monitoring SSC in the Mississippi River. Data collection and post-processing with the LISST-200X is only a few minutes when compared to traditional days necessary for physical sediment sampling. Once start conditions are met, (i.e. manual switch, time or depth start) the LISST-200X can be directly submerged and data collection starts immediately and continuously. LISST-200X requires little labor when collecting data, unlike physical samplers, where water samples must be unloaded from the sampler after each data collection point. At the end of data collection, the LISST-200X only requires a few minutes to download data from the instrument and process raw data in the provided LISST-SOP200X software.

The LISST-200X does require initial site calibration with physical samples, however after calibration, data collection time is cut into a fraction of the time because physical sampling is not necessary. The calibrated SSC from the LISST-200X had highly accurate results for both the two stations chosen in the MMR. Additionally, the LISST-200X provided high resolution SSC and PSD distributions which could be used to further understand the complexity and variability in SSC distributions in a large river, such as the Mississippi. The LISST-200X usability is limited due to being unable to accurately measure data when the water is too turbid. Materials that cause turbid water include clay, silty, fine inorganics and organics, algae, and other microscopic organisms. The SSC and associated turbidity of water the in Mississippi River can be extremely high at times. The LISST-200X therefore may not always be used to estimate

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SSC in the Mississippi River. An additional drawback of the LISST-200X is the limited spatial extents relative to remote sensing methods.

SSC estimation with remote sensing is not limited by water turbidity. Surface reflectance-SSC models, however are greatly affected by presence of clouds. Cloud coverage, one of the biggest downfalls in monitoring SSC with remote sensing, was exhibited in this study. The presence of clouds can sometimes cover hundreds of miles of the Mississippi River on a single date. Cloud coverage, combined with the temporal resolution of the Landsat satellites can leave huge gaps in data when monitoring SSC. However, the image extents and 30 meter by 30 meter spatial resolution of the Landsat satellite images is one of the greatest benefits of using remote sensing for SSC monitoring. Despite the lesser accuracy of surface reflectance-SSC compared to the LISST-200X SSC, the remote sensing surrogate method was still able to estimate the SSC gradient across the Mississippi River caused by the Missouri River inflow. Surface reflectance-SSC was obtained without entering the field, making it a completely labor-free option. Additionally, the accessibility of Landsat remote sensing images makes it a powerful tool for research and monitoring for the Mississippi River basin.

6.2 Conclusions

The following final conclusions were made on this study:

- laser diffraction was an effective surrogate method for measuring SSC when used in a large river such as the Mississippi River;
- from the LISST-200X data, temporal variability was observed in SSC at stationary points in a water column (standard deviations ranging from 15.1 to 60.0 and 3.0 to 12.1 for Chester and St. Louis, respectively);

- the LISST-200X instrument may not have been fully measuring the total SSC due to the instrument's particle measurements range;
- the remote sensing surrogate method estimated SSC at lower concentrations best (St. Louis dataset), which supports the theory that surface-reflectance-SSC may not be fully capturing SSC in an entire water column;
- 5. the remote sensing surrogate method using Landsat imagery is not an ideal method for continuous SSC monitoring on the Mississippi River due its limited temporal resolution (16 days between measurements) and dependence on clear weather conditions; however, these limitations could be overcome by utilizing terrestrial-based remote sensing equipment;
- the LISST-200X SSC (13.1%) had a lower percent error when predicting SSC than the Landsat surface-reflectance SSC (27.3%);
- 7. when comparing Rouse profiles created from experimentally and theoretically derived Rouse numbers, the theoretical Rouse number ($P_t = 0.0285$) was smaller than the experimental Rouse Numbers ($P_{e,avg} = 0.145$ and $P_{e,50\%-Q \text{ width}} = 0.0971$) for Chester and the experimental Rouse number profiles matched the SSC profile the best while for St. Louis, theoretical and experimental Rouse numbers differed minimally ($P_t=0.0238$, $P_{e,avg}=0.0253$, $P_{25\%-Q \text{ width}} = 0.0176$, and $P_{75\%-Q \text{ width}} = 0.0345$) but all Rouse number profiles did not match the SSC profile well.
- determining depth-integrated SSC may be improved if the Rouse equation with a best fit Rouse number is incorporated with an estimate of the SSC at the water surface.

6.3 Future Research Recommendations

Future research may be done to address multiple issues faced when using Landsat satellites. The effect of cloud coverage combined with the temporal resolution of Landsat could cause large gaps in the SSC dataset. To address these problems, a terrestrial multispectral camera could be used to collect images that can then be correlated to SSC, like the Landsat surface reflectance-SSC correlation. Terrestrial multispectral cameras can be either mounted at a USGS gaging station or attached to a drone for data collection. A mounted terrestrial multispectral camera would eliminate the time required for physical data collection because it could be programmed to take periodic images that could remotely accessed. Multispectral cameras as a surrogate method of estimating SSC could also provide a finer spatial resolution than Landsat's 30 m by 30 m resolution.

Appendix A: Physical Water Sample Data

Table 18: Summary of SSC analysis of physical water samples for the 25%-discharge width locations at St. Louis.

Stream	n and Location:	Mississippi River at St. Louis						
Date:		8/1/2018	8/1/2018	8/1/2018	8/1/2018	8/1/2018	8/1/2018	
Time:		1:25 PM	1:36 PM	1:28 PM	1:30 PM	1:31 PM	1:33 PM	
Gage Height/ Q:		5' Depth	10' Depth	15' Depth	20' Depth	25' Depth	30' Depth	
	Sta/btl #:	523 - P	523	523	523	523	523	
	Depth:	32'	32'	32'	32'	32'	32'	
OF E	Gross (g)	1036.72	1020.5	889.31	991.96	984.96	1005.22	
WEIGHT SAMPL	Tare (g)	58.4	58.86	60.93	60.49	58.76	59.48	
	Net (g)	978.32	961.64	828.38	931.47	926.2	945.74	
Container no.		1	2	3	4	5	6	
[.	Gross (g)	112.57	109.71	125.12	107.79	106.29	111.57	
ΟIN	Tare (g)	112.46	109.61	125.02	107.68	106.19	111.47	
HT ME	Net (g)	0.1055	0.1057	0.0943	0.1175	0.0983	0.0998	
WEIG	D.S. Correction	0.0187	0.0309	0.0162	0.0314	0.0274	0.0217	
	Net (g)	0.0868	0.0748	0.0781	0.0861	0.0709	0.0781	
Concentration (ppm)		88.71	77.77	94.25	92.44	76.59	82.58	
Concentration (mg/L)		88.71	77.77	94.25	92.44	76.59	82.58	

Stream and Location:		Mississippi River at St. Louis							
Date:		8/1/2018	8/1/2018	8/1/2018	8/1/2018	8/1/2018	8/1/2018		
Time:		1:37 PM	1:38 PM	1:40: PM	1:41 PM	1:42 PM	1:44 PM		
Gage Height/ Q:		5' Depth	10' Depth	15' Depth	25' Depth	30' Depth	35' Depth		
Sta/btl #:		1247	1247	1247	1247	1247	1247		
D	epth:	37'	37'	37'	37'	37'	37'		
HT LE	Gross (g)	961.87	996.68	1010.12	840.01	944.39	1011.62		
WEIG OF SAMP	Tare (g)	59.08	58.33	59.28	59.78	59.61	58.39		
	Net (g)	902.79	938.35	950.84	780.23	884.78	953.23		
Container no.		7	8	9	10	11	12		
<u>ل</u> ت .	Gross (g)	102.69	103.02	118.00	109.89	98.23	101.57		
O N	Tare (g)	102.53	102.84	117.83	109.73	98.03	101.39		
WEIGHT	Net (g)	0.1646	0.1771	0.1643	0.1606	0.1972	0.1811		
	D.S. Correction	0.0382	0.0451	0.0492	0.0539	0.0553	0.0556		
	Net (g)	0.1264	0.1319	0.1151	0.1066	0.1419	0.1255		
Concentration (ppm)		139.98	140.60	121.02	136.67	160.38	131.66		
Concentration (mg/L)		139.98	140.60	121.02	136.67	160.38	131.66		

 Table 19: Summary of SSC analysis of physical water samples for the 75%-discharge width locations at St. Louis.



Appendix B: Vertical SSC Profiles

Figure 37: LISST-200X vertical SSC profiles at 90%- and 70%-discharge width locations for Chester, IL.



Figure 38: LISST-200X vertical SSC profiles for the 50%- and 30%-discharge width locations at Chester, IL.



Figure 39: LISST-200X vertical SSC profile for the 10%-discharge width location at Chester, IL.



Figure 40: LISST-200X vertical SSC profile for 95%- and 85%-discharge width locations at St Louis, MO.



Figure 41: LISST-200X vertical SSC profiles for 75%- and 65%-discharge width locations at St. Louis, MO.



Figure 42: LISST-200X vertical SSC profiles for 55%- and 45%-discharge width locations at St. Louis, MO.



Figure 43: LISST-200X vertical SSC profiles for the 35%- and 25%- discharge width locations at St. Louis, MO.



Figure 44: LISST-200X vertical SSC profiles for the 15%- and 5%-discharge width locations at St. Louis, MO.

Appendix C: Particle Size Distributions



Figure 45: PSD curve for Chester, IL sample at 10- foot depth.



Figure 46: PSD curve for Chester, IL sample at 15-foot depth.





Figure 47: PSD curve for Chester, IL sample at 20-foot depth.



Figure 48: PSD curve for Chester, IL Sample at 25-foot depth.



Figure 49: PSD curve for Chester, IL sample at 30-foot depth.



Figure 50: PSD curve for Chester, IL sample at 35-foot depth.



Figure 51: PSD curve for St. Louis, MO 25%-discharge width location sample at 10-foot depth.



Figure 52: PSD curve for St. Louis, MO 25%-discharge width location sample at 15-foot depth.



Figure 53: PSD curve for St. Louis, MO 25%-discharge width location sample at 20-foot depth.



Figure 54: PSD curve for St. Louis, MO 25%-discharge width location sample at 25-foot depth.



Figure 55: PSD curve for St. Louis, MO 25%-discharge width location sample at 30-foot depth.



Figure 56: PSD curve for St. Louis, MO 75%-discharge width location sample at 10-foot depth.



Figure 57: PSD curve for St. Louis, MO 75%-discharge width location sample at 15-foot depth.



Figure 58: PSD curve for St. Louis, MO 75%-discharge width location sample at 25-foot depth.



Figure 59: PSD curve for St. Louis, MO 75%-discharge width location sample at 30-foot depth.



Figure 60: PSD curve for St. Louis, MO 75%-discharge width location sample at 35-foot depth.



Appendix D: Experimental Rouse Number Calibrations

Figure 61: Power regression curve for experimental Rouse number at 10%-discharge width location at Chester.



Figure 62: Power regression curve for experimental Rouse number at 30%-discharge width location at Chester.



Figure 63: Power regression curve for experimental Rouse number at the 70%-discharge width location at Chester.



Figure 64: Power regression curve for experimental Rouse number at the 90%-discharge width location at Chester.



Figure 65: Power regression curve for experimental Rouse number at the 5%-discharge width location at St. Louis.



Figure 66: Power regression curve for experimental Rouse number at the 15%-discharge width location at St. Louis.



Figure 67: Power regression curve for experimental Rouse number at the 25%-discharge width location at St. Louis.



Figure 68: Power regression curve for experimental Rouse number at the 35%-discharge width location at St. Louis.



Figure 69: Power regression curve for experimental Rouse number at the 45%-discharge width location at St. Louis.



Figure 70: Power regression curve for experimental Rouse number at the 55%-discharge width location at St. Louis.



Figure 71: Power regression curve for experimental Rouse number at the 65%-discharge width location at St. Louis.



Figure 72: Power regression curve for experimental Rouse number at the 75%-discharge width location at St. Louis.



Figure 73: Power regression curve for experimental Rouse number at the 85%-discharge width location at St. Louis.



Figure 74: Power regression curve for experimental Rouse number at the 95%-discharge width location at St. Louis.

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