IN SITU CHARACTERIZATION OF SEDIMENT OXYGEN DEMAND ACROSS THE SPECTRUM OF NON-RESUSPENSION TO FULL RESUSPENSION WITH VARYING BED SHEAR STRESS

BY

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THESIS

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**ABSTRACT**

Sediment oxygen demand (SOD) can be a significant oxygen sink in various types of water bodies, particularly slow-moving waters with substantial organic sediment accumulation. In most settings where SOD is a concern, the prevailing hydraulic conditions are such that the impact of sediment resuspension on SOD is not considered. However, in the case of Bubbly Creek in Chicago, Illinois, the prevailing slack water conditions are interrupted by infrequent intervals of very high flow rates associated with pumped combined sewer overflow (CSO) during intense hydrologic events. These events can cause resuspension of the highly organic, nutrient-rich bottom sediments, resulting in precipitous drawdown of dissolved oxygen (DO) in the water column. While many past studies have addressed the dependence of SOD on near-bed velocity and bed shear stress prior to the point of sediment resuspension, there has been limited research that has attempted to characterize the complex and dynamic phenomenon of resuspended-sediment oxygen demand. To address this issue, a new in situ experimental apparatus referred to as the U of I Hydrodynamic SOD Sampler was designed to achieve a broad range of velocities and associated bed shear stresses. This allowed SOD to be analyzed across the spectrum of no sediment resuspension associated with low velocity/bed shear stress through full sediment resuspension associated with high velocity/bed shear stress.

The current study split SOD into two separate components: (1) $SOD_{NR}$ is the sediment oxygen demand associated with non-resuspension conditions and is a surface sink calculated using traditional methods to yield a value with units (g/m²/day); and (2) $SOD_R$ is the oxygen demand associated with resuspension conditions, which is a volumetric sink most accurately characterized using non-traditional methods and units that reflect suspension in the water column (mg/L/day). In the case of resuspension, the suspended sediment concentration was analyzed as a function of bed shear stress, and a formulation was developed to characterize $SOD_R$ as a function of suspended sediment concentration in a form similar to first-order biochemical oxygen demand (BOD) kinetics with Monod DO term.

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The results obtained are intended to be implemented into a numerical model containing hydrodynamic, sediment transport, and water quality components to yield oxygen demand varying in both space and time for specific flow events. Such implementation will allow evaluation of proposed Bubbly Creek water quality improvement alternatives which take into account the impact of SOD under various flow conditions. Although the findings were based on experiments specific to the conditions in Bubbly Creek, the techniques and formulations developed in this study should be applicable to similar sites.
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Chapter 1. INTRODUCTION

1.1 Motivation and Objectives

Illinois state regulatory agencies are considering implementation of more stringent dissolved oxygen (DO) standards for the Chicago area waterways. The costs and benefits of the specific management options required to achieve compliance with the proposed standards have been analyzed, and among the options deemed most feasible are river flow augmentation and supplemental aeration (CTE|AECOM, 2007). One proposed solution calls for construction of three side-stream elevated pool aeration (SEPA) stations in Bubbly Creek at a cost of several million dollars. Effects not fully considered in the previous analyses are the potential increase of sediment oxygen demand under non-resuspension conditions (hereafter referred to as $SOD_{NR}$) with increased flow rates; and the potential to resuspend sediment which could induce a much larger sediment oxygen demand associated with resuspension (hereafter referred to as $SOD_R$). There is a strong possibility that DO added through the proposed management strategies could be consumed through increased SOD, resulting in less benefit to water column DO concentrations than expected. This study was motivated by the need to evaluate the management strategies with respect to flow velocity dependent effects on SOD.

Previous studies have characterized $SOD_{NR}$ of various waterways in the Chicago area. Of particular significance are those studies performed by Thomas Butts of the Illinois State Water Survey (1974); and Irwin Polls and Charles Spielman of the Metropolitan Sanitary District of Greater Chicago (1977). While extensive data was gathered, their efforts did not focus on Bubbly Creek; and their sampling protocol characterized $SOD_{NR}$ under a relatively static water condition. Research performed in the intervening years has enumerated the hydrodynamic influences on $SOD_{NR}$, and therefore sampling performed using traditional methods under relatively static water conditions may significantly underestimate the actual $SOD_{NR}$. The primary objectives of the current study have been to characterize $SOD_{NR}$ as a function of water...
velocity / bed shear stress; to characterize the bed shear stress threshold at which sediment resuspension is initiated; to characterize the magnitude of resuspension as bed shear stress increases; and to characterize $SOD_R$ as a function of the concentration of sediment in suspension. The ultimate goal is to incorporate these findings into a numerical water quality model so that proposed management alternatives can be better evaluated.

An adequate formulation for $SOD_R$ for use in water quality modeling does not currently exist. One water quality modeling strategy for the analysis of resuspended highly organic sediment is to treat it as a direct source of BOD, as originally postulated by Dobbins (1964) and for which a modeling framework was proposed by Motta et al. (2010). A goal of the current study with respect to the case of sediment resuspension is to provide field experimental data to confirm or deny the validity of that assumption for the case of Bubbly Creek in Chicago, Illinois; and, if it is found to be valid, to directly quantify appropriate parameters for its implementation in a water quality model. The hypothesis to be tested in this study with respect to $SOD_R$ is that the concentration of suspended sediment can be treated as a surrogate of BOD, and the DO sink term can consequently be expressed in a formulation parallel to first-order BOD kinetics with Monod DO term.

1.2 State of the Science of SOD Analysis: Hydrodynamic Influences

Sediment oxygen demand is the uptake of dissolved oxygen from the water column through biological and chemical oxidation processes that occur within the sediment (Hondzo and Steinberger, 2008). SOD can be a significant sink in a DO mass balance, and the negative effects of low DO concentrations on aquatic life have generated the need to accurately measure this sink. Established methods of measuring SOD under no sediment resuspension conditions are presented in Bowman and Delfino (1980) and Cerco et al. (1992), which include both in situ and laboratory techniques. More recent developments include a non-invasive measurement technique known as eddy correlation, where DO and vertical velocity fluctuations are measured simultaneously near the bed to calculate the DO flux between water column and sediment bed (Berg et al., 2003). The most prevalent of the in situ methods involves placing an open-
bottomed chamber on the sediment bed, while water is circulated in the chamber and DO concentration is measured through time (e.g., Murphy and Hicks, 1986). This type of closed measurement system results in the experimental artifact of creating unnatural hydrodynamic conditions and isolating the control volume from the ambient turbulence characteristic of the water body; on the other hand, it allows for great experimental control to evaluate the influence of hydrodynamics.

The hydrodynamic influence on DO fluxes across the sediment-water interface can be elucidated by quantifying DO production, consumption and mass transport processes within the water column and the sediment. Alternatively, the same processes can be quantified for chemical constituents that are oxidizable by DO (DiToro, 2001). From the DO viewpoint, much research has focused closely on diffusion across the thin diffusive sublayer at the sediment-water interface as a potentially rate-limiting process. The DO flux is commonly evaluated as the product of a mass transfer coefficient ($\beta$) and the concentration difference across the diffusive sublayer ($\Delta C$) (Boudreau and Guinasso, 1982). The hydrodynamic conditions control the value of $\beta$, as numerous studies have shown both empirically and theoretically that $\beta$ is a function of the shear velocity ($\nu$) and the Schmidt number ($\text{Sc} = \nu/D$, where $\nu$ is the fluid kinematic viscosity and $D$ is the molecular diffusion coefficient of DO); see O’Connor et al. (2009) for a list of such studies. On the other hand, sediment processes have the largest influence on $\Delta C$, as the net rate of DO consumption within the shallow sediment relative to the rate of DO delivery through the diffusive sublayer controls the concentration at the interface. Processes involved in DO consumption in the sediment include mineralization of particulate organic matter to produce soluble intermediates that can be consumed through bacterial metabolism or chemical oxidation (DiToro, 2001). DO is generally present as an oxidizing agent only very close to the sediment surface (typically at a depth in the sediment $< 1$ cm) and mass transport of oxygen and reduced constituents in the sediment generally occurs through diffusive processes in the pore water, except in highly permeable sediments where advection can be significant (Janssen et al., 2005). Nakamura and Stefan (1994) developed relations for both the water-side diffusion-controlled process and the sediment-side DO consumption processes. Their theory shows that at very low flow velocities all DO that is delivered through the diffusive sublayer is
rapidly consumed in the sediment; with increasing velocity, the DO flux increases asymptotically toward a maximum value, reached at moderate velocities, when the DO uptake rate in the sediment limits further increases in the flux. Numerous experimental studies have confirmed this general theoretical construct (e.g. Mackenthun and Stefan, 1998; Arega and Lee, 2005).

The hydrodynamic influence on DO flux has also been approached from the viewpoint of unsteadiness in the near-sediment region, under the recognition that DO concentrations and flow velocity near the wall undergo fluctuations due to turbulence. Although the previously mentioned diffusive sublayer lies within the viscous sublayer where viscous effects dominate turbulent effects on flow momentum transfer, turbulent fluctuations have been shown to be significant, and the frequency of turbulent fluctuations can be calculated as a function of $u^*$ and $\nu$ (Gunderson and Jorgensen, 1990; O’Connor and Hondzo, 2008). Hondzo (1998) postulated that small scale quasi-streamwise vortices generated in the near-wall region result in infusions of high DO concentration water into the diffusive sublayer with associated ejections of low DO concentration water into the overlying water column. The spatial and temporal variability of these coherent turbulent structures can consequently have a substantial effect on the DO flux. The experiments of O’Connor and Hondzo (2008) and O’Connor et al. (2009) have provided evidence of diffusive sublayer turbulence influence on DO flux. Larger-scale outer-region eddies impinging on the near-wall region may also result in turbulence in the diffusive sublayer, although this influence is still largely unknown (Robinson, 1991).

The aforementioned studies focused on the hydrodynamic influence on oxygen uptake prior to the point of sediment resuspension. However, less work has been devoted to the analysis of high flow velocity effects on oxygen uptake caused by sediment resuspension. This is partly because many water bodies with deep organic sediment beds are characterized by prevailing hydraulic conditions that are not conducive to resuspension; but it is also due to the inherent difficulty in characterizing this dynamic phenomenon. There have been many studies undertaken to quantify sediment resuspension (e.g. Young, 1977; Lopez and Garcia, 2001), fewer studies to quantify oxygen uptake associated with sediment resuspension (e.g. Berg,
1970; Wainwright, 1987), and a very limited few that have attempted to couple the two facets (e.g. Briskin and García, 2002; Schlaeger et al., 2002). With respect to the first category, the types of laboratory and in situ methods to study sediment resuspension as a function of bed shear stress are outlined in a literature review prepared by Liem et al. (1997), which include various types of flumes and submerged jet tests. As regards the second category of studies, Berg (1970) analyzed in laboratory solutions of resuspended sediment using a respirometer and identified a linear relationship between the maximum oxygen uptake rate and the concentration of volatile suspended solids (VSS). Butts (1974) gave some attention to resuspension effects in the field, noting a very sharp initial oxygen drawdown associated with resuspension upon placement of the experimental chamber on the bed, and the resuspension oxygen uptake rate was quantified as a 10-fold increase over quiescent conditions. Studies included in Cerco et al. (1992) noted that sediment resuspension increases the oxygen uptake rate, but it is generally regarded as simply an obstacle to accurate SOD measurements. More recent developments to build a suitable experimental apparatus for coupling sediment resuspension with oxygen uptake include the related work of Liem et al. (1997), Jubb et al. (2001) and Schlaeger et al. (2002). The apparatus in these studies contains a 10 cm-diameter enclosed cylinder with a near-bed propeller that generates shear stresses as high as 6.5 N/m² (Schlaeger et al., 2002) and allows measurement of DO and other dissolved constituents. Although these studies provide some quantification of the oxygen uptake rate associated with resuspended sediment, the need exists for a more dynamic formulation that can be implemented in a water quality model that accounts for transport and fate of sediments put into suspension and the impact on DO concentrations.
1.3 Study Area

1.3.1 A Brief Physical Description of Bubbly Creek

Bubbly Creek is a tributary of the South Branch of the Chicago River (SBCR). It is approximately 2000 m in length, 44 m in average width, and varies between 1.2 m and 3.6 m in depth (excluding the deeper and wider turning basin). A large scale plan view of the current configuration of Bubbly Creek is shown on Figure 1.1, which identifies landmarks along the stream that are referenced throughout this document. An overview showing the location of Bubbly Creek in the context of a larger view of the Chicago River system is included as Figure A.1 in Appendix A. More detailed figures at smaller scale showing bathymetry and stream profiles are also included in Appendix A.

Sediment depth (between the sediment surface and native subsoil) has been measured between 1.68 and 5.12 meters thick at various locations along the creek (CDM, 2005). The deep bed of organic, nutrient-rich sediments is a result of past and ongoing waste discharges. Large quantities of blood, offal, hair, and other animal wastes were discharged to Bubbly Creek from the Union Stock Yards from 1865 through approximately 1939 (USACE, 2007). Raw sewage from the municipal sewer system was discharged prior to implementation of wastewater treatment facilities (Hill, 2000), and CSO continues to be intermittently discharged by the Racine Avenue Pumping Station (RAPS) located at the head of the existing alignment of Bubbly Creek (Figure 1.1). Ongoing improvements to the sewer infrastructure in the Chicago area have reduced CSO events to an average of 15 per year in the 10-year period from 2000-2009, with a minimum of 5 events and a maximum of 23 events in a calendar year during this period. RAPS has the capacity to pump up to 170 m$^3$/sec and data provided by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) indicates that in the period from January 1, 2007 through May 21, 2010, the average discharge during CSO events was 37.8 m$^3$/sec with an 11.5-hour average duration. Noticeable flows are not experienced in Bubbly Creek except when RAPS discharges CSO into the creek during large precipitation events; during dry weather periods, Bubbly Creek is a stagnant backwater of the SBCR.
A profile view of Bubbly Creek showing the location of the top of sediment and the base of the sediment (in other words, the top of the native subsoil) is included as Figures A.12 in Appendix A. The data reveals that the top of native subsoil varies between an elevation of -4.95 and -7.87 meters relative to the Chicago City Datum (CCD). It is unlikely that these top of subsoil elevations represent the natural streambed prior to human settlement and consequent waste deposition. According to the US Army Corps of Engineers (USACE, 2007), in the past “the channel was systematically deepened and widened to allow for drainage and disposal of wastes from the nearby meatpacking industries.” This is a viable explanation for the depth to native subsoil, which has allowed for such a substantial accumulation of sediment. The bathymetry provided on Figures A.3 through A.11 in Appendix A represents the top of sediment for the entire plan view of the stream. To derive an approximate depth of the waste-derived sediment at any particular location, the bathymetric elevation of the top of sediment can be compared to the mean elevation of the base of sediment, which is approximately -6.4 meters (CCD).

1.3.2 A Brief History of Bubbly Creek

Before being given the name Bubbly Creek, the stream was originally the South Fork of the South Branch of the Chicago River. The South Fork flowed east and north, joining with the West Fork to form the South Branch of the Chicago River. The South Branch flowed in a general easterly direction to eventually join with the North Branch to form the Main Stem of the Chicago River, which discharged to Lake Michigan. An illustration of the pre-settlement alignment of the upper South Branch system is provided in Figure 1.2, which includes some present-day features for spatial reference. Figures 1.3 and 1.4 illustrate some of the alterations described in the following chronology, which was condensed from Hill (2000), unless otherwise indicated:

1848: Construction of the Illinois & Michigan Canal was completed. Approach channels to the upper canal were located at the junction of the South Fork and the West Fork of the South Branch, altering the configuration of the lower South Fork. (See Figure 1.3).
Mid-1800s to 1865: Slaughterhouses and meatpacking plants were distributed in an unconsolidated fashion along the South Branch and South Fork. These industries discharged waste directly to the streams, contributing to the poor water quality throughout the Chicago River system.

1865: The stock yards were consolidated into a single region known as the Union Stock Yards south of the current head of Bubbly Creek.

~1866: A ditch known as the Stock Yards Slip was constructed that connected to the South Fork. (See Figure 1.3). Waste from the stock yards was discharged to the ditch. Foul conditions in the South Fork resulted in it earning the colloquial name “Bubbly Creek”. Ed Lace, contributing author of Hill (2000), relays the following anecdote of conditions in the early 20th century, resulting primarily from the waste discharge by the Stock Yards:

“Nothing yet devised by the city regarding sewage control could help the South Fork, as most of its flow was not water. As the offal settled to the bottom it began to rot. Grease separated and rose to the surface. Bubbles of methane formed on the bed of the river and rose to the surface, which was coated with grease. Some of these bubbles were quite large and when they burst a stink arose. There were many local names for this part of the river, most unprintable. The one that stuck was Bubbly Creek.”

The creation of the Stock Yards Slip formed a fork in Bubbly Creek. As a result, the Stock Yards Slip was also referred to as the “East Arm” of the South Fork; and the natural west-to-east alignment of the upper South Fork was also referred to as the “West Arm”.

Late 1800s to 1916: Raw sewage from sewer mains along Damen Avenue and Ashland Avenue discharged directly to the “West Arm” of Bubbly Creek.

Late 1800s to 1926: Raw sewage from sewer mains on Halsted Street discharged to the Stock Yards Slip.

1900: The Sanitary and Ship Canal was completed, thereby reversing the flow direction of the South Branch (the receiving waterway), such that flow at the terminus of Bubbly Creek was conveyed west instead of east during normal flow conditions.
1904-1907: The turning basin was constructed at the junction of the South Fork and West Fork, altering the configuration of lower Bubbly Creek.

1916: The Sanitary District of Chicago completed the Stockyards Intercepting Sewer, which provided a new outlet for city sewers along Damen and Ashland Avenue. (It is presumed that the new outlet was further downstream along Bubbly Creek at Racine Avenue.) After the completion of the new sewer, the upper West Arm was filled down to Ashland Avenue.

1923: Congress declared the remainder of the West Arm downstream to 39th Street non-navigable, and that reach was consequently filled.

1921-1926: An intercepting sewer was constructed by the City of Chicago that provided for sewage to bypass the Stock Yards Slip and discharge directly into Bubbly Creek at Racine Avenue.

1933: The Illinois & Michigan Canal was officially closed. The approach channels at the turning basin were filled.

1939: Racine Avenue Pumping Station was constructed. Raw sewage continued to be discharged to Bubbly Creek while the Stickney Water Reclamation Plant became fully operational.

~1940: The Stock Yards Slip was filled; exact date uncertain.

1942: The Stickney Water Reclamation Plant was opened, and Racine Avenue Pumping Station began pumping sewage to Stickney for treatment rather than discharging raw sewage directly to Bubbly Creek during normal flow conditions.

1942-1985: Bubbly Creek continued to receive raw sewage, but only during combined sewer overflow (CSO) events, which occurred approximately 50 times per year.

1971: The Union Stock Yards closed.
1985: The first segment of the Tunnel and Reservoir Plan (TARP) was completed and operational.

1985-Present: More segments of the Tunnel and Reservoir Plan went into operation. CSO events from the Racine Avenue Pumping Station were gradually reduced, reducing the waste load received by Bubbly Creek.

1.3.3 Summary of Previously Collected $SOD_{NR}$ and Other Sediment Data

Various organizations have performed $SOD_{NR}$ sampling within Bubbly Creek, the Chicago Area Waterway System, and the upper Illinois River in the past. A brief summary of previous findings is provided for reference.

  - Sampling was performed on the upper Illinois River in the Peoria pool, Starved Rock pool, and Dresden Island pool; the closest to Chicago being the latter, which extends from 5 to 15 miles downstream of the Lockport dam.
  - The $SOD_{NR}$ values progressively decreased in the downstream direction from pool to pool.
  - For the Dresden Island pool (closest to Chicago), 12 experimental stations were sampled with $SOD_{NR20}$ values that varied between 1.25 and 8.08 g/m$^2$/day; the mean value was 3.86 g/m$^2$/day. ($SOD_{NR20}$ refers to $SOD_{NR}$ values normalized to a temperature of 20°C.)

- Irwin Polls and Charles Spielman (1977) of the Metropolitan Sanitary District of Greater Chicago
  - Sampling was performed throughout the Chicago Area Waterway System, including a sampling station at Bubbly Creek.
  - An $SOD_{NR20}$ of 3.42 g/m$^2$/day was measured on 09/27/76 at the Archer Avenue bridge. An $SOD_{NR20}$ of 4.42 g/m$^2$/day was measured on 12/06/76 at the Archer Avenue bridge. Both results were obtained in a laboratory from sediment
sampled in the field; laboratory analysis was required due to the low DO level in Bubbly Creek.

- Throughout the Chicago Area Waterway System, $SOD_{NR20}$ measurements varied between 1.23 to 23.32 g/m$^2$/day; the mean value was 6.98 g/m$^2$/day.

  - An $SOD_{NR20}$ of 3.26 g/m$^2$/day was measured near the east bank of Bubbly Creek at 33$^{rd}$ Street.
  - An $SOD_{NR20}$ of 1.38 g/m$^2$/day was measured near the west bank of Bubbly Creek in the turning basin.
  - Throughout the Chicago Area Waterway System, $SOD_{NR20}$ measurements varied between 0.23 to 4.81 g/m$^2$/day; the mean value was 2.01 g/m$^2$/day.

The methods used to measure $SOD_{NR}$ in these previous studies are briefly outlined in Section 2.2 of this document.

In addition to $SOD_{NR}$ data, general sediment characteristics have also been obtained in Bubbly Creek. The USACE obtained the most comprehensive set of sediment data (CDM, 2005), which included sample cores from thirteen locations; and five surface grab samples obtained with a Ponar dredge. For each of these samples, various chemical and physical properties were analyzed. In the current study, the grain-size distribution and specific-gravity determinations from the USACE report were utilized in the sediment transport calculations presented later in this document. The following information was extracted from Motta (2008), which summarizes the most relevant sediment data from the USACE report and various other studies.

- **Sediment depth**: according to the analysis by USACE (April 2004) along the whole length of Bubbly Creek (cores and grab samples, USACE, 2005), sediment depths ranged between 1.68 to 5.12 m. At the turning basin, the average sediment depth measured by UIC (Yin et al., 2007) was 5.38 m in October - November 2005 (maximum 7.07 m, minimum 3.71 m);

- **Porosity**: at the turning basin, according to the 2005 analysis by UIC (Yin et al., 2007), the sediment porosity was on average 76.51% for the cores and 87.09% for the surface grabs;
• **Particle density**: UIC (Yin et al., 2007) found a value of 2392 kg/m$^3$ for the cores and 2423 kg/m$^3$ for the surface grabs at the turning basin. According to the analysis by USACE along the whole length of Bubbly Creek in April 2004 (cores and grab samples, USACE, 2005), the specific gravity of the particles was on average 2.10, with maximum and minimum values respectively of 2.57 and 1.37;

• **Particle size**: from the 2004 study by USACE (cores and grab samples, USACE, 2005), the particle size of the particles, expressed as median size $D_{50}$, was on average 82 μm (fine sand-coarse silt size), with maximum and minimum values respectively of 258 μm and 20 μm. A “mean” granulometric curve was characterized by 5.43% gravel, 49.15% sand, 26.74% silt and 18.68% clay. Results by the MWRDGC (2008) at Archer Avenue confirmed these ranges;

• **Organic matter (OM) content of the bed sediments**: UIC in 2005 measured a value of 152.66 mg/g for the cores and 132.70 mg/g for the surface grabs at the turning basin (Yin et al., 2007). For USACE (2005), the mean value for the Total Organic Carbon (TOC) along the whole length of Bubbly Creek in 2004 was 97.205 mg/g, with a maximum value of 170 mg/g and a minimum value of 5.9 mg/g. USEPA (Collier and Cieniawski, 2003) and the MWRDGC (2008) confirmed, for several locations in the creek, the order of magnitude reported by UIC and USACE;

• **Chemical oxygen demand (COD)**: while all agencies’ data substantially agree about the organic content of the sediments, relevant discrepancies are observed in terms of quantification of COD. For USACE (2005) the mean value for COD along the whole length of Bubbly Creek in April 2004 (cores and grab samples) was 2.221 mg/g, with a maximum value of 6.6 mg/g and a minimum value of 0.38 mg/g. UIC (Yin et al., 2006) reports data by CDM for COD at the turning basin and along Bubbly Creek (average) which are both around 1.2 mg/g. On the other hand, according to the measurements by USEPA (Collier and Cieniawski, 2003) downstream from the I-55 crossing in October 2000, the COD was on average 363.25 mg/g, with maximum and minimum values of 682 mg/g and 193 mg/g.”
AT THIS DOGLEG, THE STREAM TRANSITIONS FROM SHALLOW AND BROAD (UPSTREAM) TO DEEP AND NARROW (DOWNSTREAM); SEE BATHYMETRY IN APPENDIX A.
Figure 1.2: Historical Condition of Upper South Branch

Figure 1.3: Modifications to Upper South Branch System Through 1939
Figure 1.4: Current Configuration of Upper South Branch System
Chapter 2. Experimental Methods

2.1 Field Experimental Apparatus and Equipment

A detailed schematic of the U of I Hydrodynamic SOD Sampler that was designed and utilized for the current study is illustrated in Figure 2.1. The total volume of water contained within the system is 51.2 liters, with 0.147 m² of exposed sediment at the chamber base. The maximum flow rate achieved during field sampling was 224 L/min. Besides the sampling apparatus, supplemental equipment included the following: a 4.3 m length johnboat with mounted winch, speed rail fittings, and 4HP motor; two 6.1 m long, 5.1 cm-diameter aluminum pipes for anchoring; a Honda EU2000 electric generator with inverter having capacity of 16.7 amperes at 120V; a Thermo Scientific vacuum pump operating at 508mmHG maximum vacuum at 115V; a Trimble AG132 GPS unit; a Lowrance LCX-15 MT Echo Sounder; a laptop computer with YSI Data Manager and Hypack GPS survey software; two 12V batteries; a 22.9 cm diameter Ponar dredge; and 1L glass and HDPE wide-mouth sample containers. Photographs of the sampling apparatus and other supplemental equipment are shown in Figures 2.2 through 2.5.

2.2 Design and Evolution of the SOD Sampler

The U of I Hydrodynamic SOD Sampler was based largely on the SOD sampler originally designed by Thomas Butts (1974) and utilized in the Chicago Area Waterway System by Irwin Polls and Charles Spielman (1977). Significant modifications were made to the Butts / Polls sampler to allow characterization of velocity-dependence and resuspension effects. It is important to describe the modifications of the U of I Hydrodynamic SOD sampler relative to the Butts / Polls sampler, along with the rationale for these modifications. The key elements of both systems are as follows: (1) a chamber that is lowered to the streambed, the base of which is open, exposing a fixed area of the sediment surface to the water that is pumped through the otherwise closed circuit; (2) a dissolved oxygen and temperature probe within the chamber; (3)

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1 Work presented herein is included in the publication Waterman et al. (In press), posted ahead of print with permission from ASCE. The author acknowledges the contributions of the coauthors of that publication: Andrew R. Waratuke, Davide Motta, Yovanni A. Cataño-Lopera, Heng Zhang, and Marcelo H. García.
a pump; and (4) hoses to connect the pumping apparatus on the surface to the chamber on the streambed. The procedures of operation of both systems are also very similar. Both systems are primed such that all free air is evacuated, and then the enclosed water is pumped in a closed loop, allowing the DO concentration to draw down as the water flows past the exposed sediment surface at the base of the chamber. Both systems assume that BOD of the enclosed ambient water is exerted at a much lower rate than the SOD, such that any DO drawdown represents primarily SOD. Both systems require that once the system is primed and evacuated of free air, no additional air is allowed to enter into the closed system – this achieves the condition of a control volume on which the SOD calculations are based.

While the above paragraph describes the similarities of the two different systems, the differences are significant. The Butts / Polls sampler characterized $SOD_{NR}$ in a relatively static water condition. The small-diameter garden hoses connecting the pump to the chamber had limited conveyance capacity, and the velocity through the chamber was intended solely as a means to ensure proper functioning of the DO probe and to maintain well-mixed conditions within the chamber. Note that the DO probe that Butts and Polls utilized was a Clark-type polarographic electrode probe, which is stirring-dependent; the specifications for those probes in use at the time required a velocity of 1 foot per second to prevent downward drift of the readings due to oxygen usage by the probe. According to Butts (1974), the mean velocity through the SOD chamber at full pumping capacity was 0.05 feet per second, although at the outlet of the garden hose where the probe was placed, the velocity exceeded the 1 foot per second specification. The hoses entered the chamber at a vertical aspect. Under the low flow operating conditions, the risk of jetting water into the chamber vertically and disturbing the exposed sediment surface was considered minimal.

The U of I Hydrodynamic SOD Sampler was required to flow at higher velocities than the Butts / Polls sampler in order to achieve the design goals of characterizing velocity-dependence and resuspension effects. The higher velocities necessitated the major modifications. A key design consideration was to establish a smooth hydrodynamic longitudinal flow condition through the chamber, so that secondary flows would not develop that would generate bed shear stresses
whose effects would be difficult to characterize. This design consideration necessitated that the inflow to the chamber be horizontal to approximate natural stream velocity conditions, which would not generally be directed downward, jetting perpendicular into to the streambed. Due to the same hydrodynamic considerations, the SOD chamber was designed with a gradual flow expansion at the inflow side of the chamber and a gradual contraction at the outflow side of the chamber to maintain as smooth a flow condition as possible. The expansion / contraction features were closed at the bottom which provided additional bearing to support the chamber on the soft sediment surface. The chamber itself has a smaller volume than the Butts / Polls system, being constructed of a half-section of 24.1 cm (9.5 inch) inside diameter Plexiglas; whereas the Butts / Polls chamber was constructed of a half-section of 35.6 cm (14 inch) diameter steel pipe. The smaller diameter allowed for higher velocities through the chamber. The remainder of the system consisted of larger elements to accommodate the higher flow rates; for example, 5.1 cm diameter hoses and pipes, higher capacity pump, etc. The U of I Hydrodynamic SOD sampler also utilized a stirring-dependent Clark-type polarographic DO probe, although the membrane materials have changed in the intervening years such that the specified minimum velocity is 0.5 ft/sec to prevent downward drift of the DO readings.

2.3 Field Data Collection Procedures

2.3.1 SOD Sampling

The initial phase of SOD field sampling in Bubbly Creek was performed during the period of August 10-12, 2009. The second phase of SOD testing was performed on September 8-9, 2009.

1. Pre-Deployment Preparation

Before deploying to the field, the SOD sampling stations were decided upon; the decision was made that the most useful data could be obtained from the locations of the previous sediment borings sampled by the USACE (CDM, 2005). Core samples through the loose sediment down to the native subsoil were obtained at thirteen stations. In addition five grab samples with a Ponar dredge were collected at stations that were typically at or near the core sample locations. The rationale for using these
locations in the current SOD characterization study was that many characteristics of the sediment profile are known, which allowed the opportunity to evaluate results under the context of the specific sediment conditions at the sampling station. The latitude-longitude values for each USACE sampling station were provided in the above-referenced document. These coordinates were imported into the GPS software being used for the field work, which allowed navigation to the specific points with a high degree of accuracy.

Prior to leaving the boat ramp on each day of sampling, the YSI Professional Plus sensor was calibrated for the DO parameter using a 1-point saturated air calibration technique.

2. Setting up on a Sample Station / Priming and Setting the SOD Sampler

Upon navigating to the sampling station using the on-boat Trimble AG132 GPS, the boat was anchored onto the station using aluminum pipes driven vertically by hand into the sediment until sufficient resistance was met to ensure the pipes would not dislodge during sampling. These pipes were attached to the boat via speed rail fittings attached to the outside of the boat. Once the boat was anchored in place, some background water quality measurements were taken with the YSI sensor to determine the ambient DO levels near the surface and at the streambed. The water depth was measured by a Lowrance LCX-15 MT Echo Sounder attached to the front of the boat. The YSI sensor was then clamped into the gasket on top of the SOD chamber, and the chamber was placed in the water. The system was primed by lowering the chamber to just below the water surface with top submerged; the vacuum pump was connected to the hose barb (part J of Figure 2.1); the check valve was opened; and the vacuum pump was powered on, drawing in ambient water from Bubbly Creek through the base of the chamber to fill the entire volume of the sampling apparatus. Most of the air was evacuated during this process. However, typically there were still some small pockets of air that remained trapped in the piping and hoses at this stage, so additional air evacuation was performed by running the centrifugal pump at the maximum flow rate with the SOD chamber still near the surface. Because flow through the SOD chamber was always at a
lower velocity than anywhere else in the system due to the larger cross-sectional area, any air bubbles tended to accumulate in the high point of the chamber. Therefore, while still running the pump, the chamber was manually rocked back and forth and inverted to evacuate air bubbles that collected. When in the inverted position, small air bubbles skimmed over the topmost edge of the opening until all air was evacuated. When bubbles no longer emerged from the chamber, the lack of air bubble entrainment was ensured by carefully examining the water pumping through the clear plastic pipe segment (part K of Figure 2.1). The SOD chamber was then turned into its normal upright position, and the centrifugal pump was turned off to create as calm a condition in the chamber as possible for the process of setting the chamber on the streambed.

The stream depth recorded from the Echo Sounder was used as a guide while lowering the chamber using the boat-mounted hoist. A graduated reel connected to the hoist line was calibrated to indicate the instantaneous depth of the bottom flange of the chamber; and graduation marks set at 30 cm (1 foot) intervals along the fire hoses were used to guide the hoses down at an even rate. This lowering process was performed in an extremely gentle manner once the reel and hose graduations indicated the chamber was nearing the bed of the stream. Typically when the streambed was first contacted and a small amount of pressure applied by the chamber cutting edge, bubbles from the bed were released, which became evident at the surface. Additional slack was given to the hoist line to allow the chamber to seat into the sediment and to ensure that any small movements of the boat during sampling would not cause the hoist line to drag the chamber out of its seated position. No sampling stations were encountered where the sediment was so loose / soft that once the hoist line was given slack, the chamber continued to sink deep into the sediment, which was a concern during the design of the sampler. Once the field staff was convinced that the chamber was fully seated, the SOD test was then ready to be initiated.
3. Running the SOD test

First, a brief description is provided of how the sampling was intended to be implemented. This will be referred to as the “optimum sampling procedure”:

(a) Prepare and seat the chamber into the streambed per the protocol above.
(b) Tighten the flow control valve (part N of Figure 2.1) to almost entirely closed. Turn on the centrifugal pump. Very gently open the gate valve until the desired flow rate for the first trial is achieved.
(c) On a given station, the first trial is the lowest flow rate to be tested. Run the test until the DO drawdown curve establishes a steady, equilibrium slope. A graph of the readings is viewed in real-time using the YSI data management software on the laptop computer, which connects to the YSI sensor via a USB connection. Any sediment resuspension that occurs during this process is noted, as indicated by the color and opacity of the water passing through the clear plastic pipe segment (part K of Figure 2.1). Establishment of the equilibrium DO drawdown slope dictates the end of the trial.
(d) The next trial is run by simply increasing the flow rate to the next flow rate to be tested. (In other words, the chamber is not picked up and reset, the system is not reprimed, etc.) The trial runs exactly as described in step (c) for the new flow rate.
(e) Additional trials are run until the pump flow rate is at the maximum value.

As expected, actual conditions in the field necessitated changes to the above sampling procedure. The optimum sampling procedure could be most closely followed when the ambient DO level in Bubbly Creek was relatively high. Under those circumstances, each trial could draw down the DO by a fraction of the total concentration, and numerous trials could be run successively. However, it was very common for the ambient DO to be very low (<2 mg/L), particularly in the morning hours. Under those circumstances, a single trial could draw down the DO to 0 mg/L, and no further trials could be run successively without unseating the chamber from the streambed, evacuating the low-DO water, re-priming the system, and resetting the chamber in a different location. This
was a time-consuming procedure that would take the majority of the day to run a relatively small number of trials. Therefore a modified sampling procedure was established for the morning hours; and a procedure closer to the optimum procedure was performed in the afternoon, where ambient DO conditions were found to be much more favorable.

Revised morning sampling procedures:

(a2) Prepare and seat the chamber into the streambed per item 2 above.
(b2) Run a single trial per items 3(b) and 3(c) above, drawing the DO all the way down to near 0 mg/L.
(c2) Initiate a “scour test” where DO is not recorded.
   (i) Increase the flow rate and run for approximately 5 minutes, noting any change in turbidity.
   (ii) Continue the procedure until the onset of the major resuspension phase.
       Once the major resuspension phase is reached, pull a water sample by connecting a hose to the top hose barb (part J of Figure 2.1); open the top check valve, allowing a small volume of water to jet through the hose into a sample container.
   (iii) Continue the above steps until the flow rate is maximized.
(d2) Unseat the chamber from the sediment, evacuate the turbid water, re-prime the system, and reset the chamber on the bed in a different location.
(e2) Run a single trial per items 3(b) and 3(c) of the optimum sampling procedure at the desired flow rate.

### 2.3.2 Water Sample Collection for Ambient Water Oxygen Uptake Rate Analysis

Ambient water oxygen uptake rate is a component of the \( SOD_{NR} \) calculations described in Chapter 3, where it is denoted as \( (dC_{DO}/dt)_{amb} \). Optimally, \( (dC_{DO}/dt)_{amb} \) would have been field-measured on ambient water at the same time that each SOD sampling trial was being performed; however, such analysis would have required a sealed system and a means of
stirring the water, and we were not equipped with this field-experimental setup before the SOD testing was initiated. Therefore on October 1, 2009, samples of water were collected for laboratory analysis. At various locations along the length of the stream, one-gallon plastic containers were submerged into Bubbly Creek such that the top of the container was 16 to 18 inches below the water surface. (Note that when priming the SOD sampler, water was brought into the system from near the surface due to the higher oxygen content and to facilitate the evacuation of air as described in the priming procedure; the intent was to gather water for laboratory analysis that was representative of the water used in the field experiments.) The one-gallon plastic containers were submerged with the lid on to prevent surface debris from being included in the samples. Once the container was submerged, the lid was opened, and all air was purged from the container as it filled with water. The samples were labeled and placed in a cooler for laboratory analysis described in Section 2.4.2.

2.3.3 Ponar Dredge Surface Sediment Sampling

The Ponar dredge is a relatively simple device that functions like a clamshell dredge. The clamshell is lowered using a rope, and tension on the rope keeps a lever mechanism engaged that maintains the clamshell in the open position. Upon settling on the bed, tension is taken off of the rope, and the lever disengages, allowing the clamshell to close under its own weight as the rope is retrieved. The closing of the clamshell scoops sediment from the surface of the streambed. It collects a sample from the sediment surface to a depth of less than 15 cm (6 inches). For the current field experiments, the Ponar dredge was lowered from the side of the boat by hand using a nylon rope. Upon raising the dredge up to the water surface, the dredge was placed in a 5-gallon bucket, and the clamshell opened, releasing into the bucket the sediment and any water that was captured while the dredge was raised. A representative sample of the mixture was collected in a 1-L container, which was then placed in a cooler containing ice. A Ponar grab sample was collected at each SOD sampling station. Any relevant features regarding sediment texture, color, odor, etc. was noted. These samples were submitted to the MWRDGC lab for analysis of percentage volatile solids. In addition to the samples collected during the SOD experiments, additional investigation was performed on
October 1, 2009, for the primary purpose of collecting fresh sediment for use in laboratory oxygen uptake experiments. The secondary purpose of the sampling was to characterize the spatial variability of sediment types in a more comprehensive sampling pattern than the limited number of SOD stations. Those grab samples were collected as described previously, except that before placing the sample in the 1-L container, the sediment texture was determined using the field method (Thien, 1979), where a small portion of the soil is kneaded between thumb and forefinger to form a ribbon. The soil was generally too saturated to form a ribbon even for the fine-grained samples. However it was possible to note the relative percentage and size of the sand component; and to estimate relative amounts of organic material characterized by a greasy texture. (Note that this was a rather unappealing task.) A photograph taken during Ponar dredge sampling is provided as Figure 2.6.

2.4 Laboratory Procedures

2.4.1 Analytic Testing by MWRDGC Laboratory

The MWRDGC made available the staff and resources of the analytic laboratory section of the Stickney Water Reclamation Plant to analyze solids and liquids collected in the field as part of this study. All laboratory analyses were performed in accordance with Section 2540 of AWWA (2005). A very brief description of the methods detailed in the manual is provided below.

Liquid Samples:

Liquid samples were analyzed for total suspended solids (TSS) and volatile suspended solids (VSS). The TSS analysis was performed by mixing the suspended sediment solution and obtaining a representative sample using a pipette; the sample volume was chosen with the intent to obtain 2.5 to 200 mg of dried residue. This sample was filtered through a glass-fiber filter disk, and the captured residue placed in a crucible and dried at 105°C for one hour. The residue was then weighed and the weight of the filter and crucible subtracted to yield a TSS concentration. The VSS represents the fraction of the solids captured in the above analysis that volatilized in an oven at 550°C.
Solids Samples:

Sediment samples collected with the Ponar dredge were analyzed for total solids by percent weight and volatile solids by percent weight. The analysis for total solids by percent weight was performed by placing a representative sample of the sediment mixture totaling 25 to 50 grams on an evaporating dish, which was then weighed. The dish with sediment was then dried at 105°C for one hour. The remainder was again weighed, and the procedure repeated until the weight change was less than 4%. After subtracting the weight of the dish, the total solids by percent weight was calculated as the initial weight divided by the final weight. The volatile solid by percent weight represents the fraction of the dried solid from the above analysis that volatilized at 550°C.

2.4.2 Oxygen Demand Laboratory Analysis

Water and sediment samples collected in the field were kept in coolers with ice until the laboratory analysis was performed, which occurred on October 2, 2009 and October 6, 2009. Laboratory analysis was performed by Ven Te Chow Hydrosystems Laboratory (VTCHL) staff utilizing the research and development laboratory at the Stickney Water Reclamation Plant. The intent of the analysis was to obtain a more comprehensive set of data on the relationship between TSS concentration and oxygen uptake rates for various types of sediment at various concentrations. Ambient water from the stream was used as the medium of the suspended sediment mixtures to ensure the presence of the type of microbial populations from the water column that would contribute to oxygen uptake in Bubbly Creek during an actual sediment resuspension event. A secondary goal of the analysis was to determine the ambient water oxygen uptake rate for use in the SOD calculations.

The specific procedures used in the analysis are described as follows:

1. Three hours prior to the initiation of the experiments, the water and sediment samples to be tested were selected, removed from the cooler, and set in an area of 20 to 25°C where they could reach an equilibrium temperature similar to laboratory conditions.
2. A YSI 5100 dissolved oxygen / temperature sensor was powered on and calibrated. The probe end of the YSI 5100 contains a rubber sleeve that fits tightly into the top of a standard 300 ml BOD bottle to seal the system from exposure to air during an oxygen uptake test. The probe also contains a stirring attachment. The YSI 5100 uses a Clark-type polarographic electrode probe, which is stirring dependent; the self-stirrer incorporated into the model ensures that adequate stirring is provided.

3. The ambient water tests were the first trials initiated on each day of sampling. The tests involved pouring approximately 400 to 500 ml of the Bubbly Creek water sample into a clean 1-L plastic container; placing the lid on the container; and then shaking vigorously to saturate the water with oxygen. The water was then poured into a clean BOD bottle to the point of overflow. The YSI 5100 probe was then inserted, causing some minor overflow and ensuring no excess air in the system. The self-stirrer was turned on and DO readings were recorded manually periodically throughout the test.

4. The tests on sediment solution involved a more complicated procedure. A representative portion of the sediment sample was obtained by gently stirring the sediment in its 1-L sample container using a stainless steel stirring rod, which distributed the liquid portion that typically had settled at the top of the container. After the gentle stirring, a fraction of the sediment was removed from the sampling container to prevent spillage and to facilitate stirring during the next step. What remained in the sample container was then stirred vigorously with the stirring rod. A stainless steel spoon was then used to dig into the container and extract a portion of the sediment from the center to bottom of the container for use in establishing the suspended sediment mixture for analysis.

For those sediments that were predominantly fine-grained, the initial trial involved mixing the maximum concentration at a volume in excess of what was needed for an individual oxygen uptake test. This allowed for a simple dilution of the excess in following steps to establish the lower concentration mixes. (Note that the sediment mixtures were so rich in organic material that there was no concern of the organics in the excess solution being depleted during the time period between mixing and later
testing to such an extent that the experiments would become rate-limited.) Mixing the initial high concentration solution was performed by placing the representative sediment in a 1000 ml glass beaker to reach approximately the 150 ml graduation line. (Volumes were noted, but were by nature not precise, because TSS concentrations would be obtained separately following the experiments through analysis by the MWRDGC analytical lab.) Then the beaker was filled with Bubbly Creek water up to the 600 ml graduation. The solution was stirred to fully-mixed and then approximately 400 ml of the mixture was poured into a 1-L plastic container. The container was closed and then shaken vigorously to saturate the solution with oxygen. The mixture was quickly poured into a BOD bottle and the YSI 5100 probe was inserted and self-stirrer engaged. DO readings were recorded manually periodically throughout the test. The tests were run until a well-defined drawdown curve was established, or until the DO was reduced to near 0 mg/L. Once the test was completed, the 300 ml mixture was poured into a new 1-L sample container and labeled for analysis. At the end of the day all samples were transferred to the analytical lab for TSS and VSS analysis.

Following the initial high concentration test, the excess solution that was mixed previously and kept in the beaker was utilized for the next test. The mixture was diluted with additional Bubbly Creek water, typically adding 2 to 3 times the volume of the remaining mixture in the beaker. Once the diluted solution was well mixed, the same procedure as described above was performed, with excess solution being kept in the beaker for the next dilution.

For those sediments that were predominantly coarse-grained (fine sand and coarser), the same procedure as above was attempted, but the rapid settling of the sand in both the beaker and the 1-L shaking container made obtaining a uniform mixture of the desired consistency while pouring into the BOD bottle nearly impossible. Therefore the modified procedure for the sandy sediment involved simply adding scoops of material directly to the BOD bottle, then aerating the water sample separately in the 1-L container and pouring into the BOD bottle to approximately half-full. The BOD bottle
was then hand-swirled to ensure that the sediment was not sticking to the bottom and could be entrained; then the BOD bottle was filled to the top, and the test proceeded as described above.

2.4.3 Grain-size Distribution and Settling Velocity Analysis with the LISST-ST

The analysis performed with the LISST-ST in the Ven Te Chow Hydrosystems Laboratory was intended to confirm and supplement sediment data from the USACE (CDM, 2005) study. The following description of the LISST-ST was extracted from Briskin and Garcia (2002).

“The LISST-ST, or Laser In-Situ Scattering Transmissometer with Settling Tube, is manufactured by Sequoia Scientific. It consists of a Plexiglas settling tube with sliding doors that seal it and a canister that contains a laser, data logger, and batteries. It measures size distribution, concentration, and settling velocity distribution. Two vertical sheets of Plexiglas inside the 5-cm settling tube create a rectangular settling volume that is 5 x 1 x 30 cm. This feature is incorporated for faster suppression of turbulence at fill-up (Sequoia). Settling velocity is measured for 8 log-spaced size classes between 1.25 and 250 μm. Using the LISST-ST instead of a standard settling tube has some advantages. Measurements are taken automatically at log-spaced intervals, meaning settling data can be obtained for the larger and heavier particles that settle out first. Using a standard settling tube requires withdrawing and sometimes dewatering samples in order to obtain concentration data. This added handling may break up aggregates that naturally form as the particles fall and collide. In contrast, the LISST-ST takes data inside the settling tube.

According to the Fraunhofer approximation, the scattering by a spherical particle of diameter d is identical to the diffraction of light by an aperture of equal diameter. This diffraction is independent of particle composition. The small-angle scattering field of an ensemble of particles is the sum of the diffraction from all the apertures, and the scattered intensities simply add, since the apertures do not interact (Pottsmith and Bhogal). In the LISST-ST, a collimated laser beam illuminates suspended particles near the bottom of the settling tube. Scattering at multiple angles is measured by a specially made silicon detector, stored in a computer, and later inverted mathematically on a PC to obtain size distribution (Sequoia). A detailed explanation of laser diffraction size analysis can be found in Agrawal et al. (1991).

In an idealized experiment, the settling column contains a fully mixed water sample in which all the particles in each size class have the same density. The solids concentration measured by the laser beam at the beginning of the test is constant and equal to the fill-up concentration. Over time, the particles that were initially at the top of the settling column reach the laser. The concentration for any size class of particles goes from the initial value to zero over a duration corresponding to the time for these particles to fall through the 6-mm laser beam (Sequoia). The settling velocity for each size class is computed by dividing the height of the settling column by the total time required by the particles to settle out of solution. Of course in reality, the solids in a water sample will seldom have a homogeneous composition. This variation in particle density smears the concentration profile. In addition, residual turbulence generated while filling up the tube may affect settling. The LISST-ST finds a settling time that minimizes the mean-square difference between the idealized and normalized history of any size class.”

In the current study, the laboratory methods used with the LISST-ST involved the following steps:
1. Calibrate the LISST-ST at the beginning of each day of sampling by running a background scatter test using tap water.

2. Add a small representative sample of the sediment to a partially filled gallon container of tap water. Shake vigorously to break up flocculated material that would naturally break apart during turbulent flow conditions.

3. Add 500 ml of tap water to a glass beaker. Pipette 5-10 ml of the solution from the 1-gallon container into the beaker until the solution was just turbid enough to remain visibility through the beaker. Swirl the beaker to mix.

4. Gently pour the solution into the settling tube on the LISST-ST. Run a 1-minute analysis for particle size distribution.

5. Decant the settling-tube. Mix another 500 ml of solution in the same manner as described in step (3). Gently pour into the LISST-ST settling tube and run a 22-hour test for settling velocity distribution.
2.5 Figures

**Figure 2.1: U of I Hydrodynamic SOD Sampler (Schematic; Side View)**

Components identified on Figure 2.1 are described as follows: (A) 10.2 cm stainless steel skirt to penetrate sediment; bounds all 4 sides of the chamber; establishes 61.0 cm x 24.1 cm area of exposed sediment within chamber. (B) 5.1 cm stainless steel flange for bearing; bounds all 4 sides of the chamber. (C) YSI Professional Plus water quality sensor; equipped with two probes: DO and pH/ORP; with internal temperature sensor; fits in rubber gasket through a hole in the top of chamber. (D) 24.1 cm-inside-diameter half-section of Plexiglas; forms top shell of chamber. (E) Flow convergence / expansion sections; half-conical; closed on bottom. (F) 5.1 cm-diameter PVC sections. (G) Quick-connect firehose fittings. (H) 5.1 cm-diameter rubber firehose; each 4.57 m length. (I) AMT centrifugal pump rated at 5.0 liters per second at 3.0 m head; with 0.56 kW electric motor. (J) Check valve for priming; vacuum pump connects here. (K) Clear plastic pipe segment for viewing turbidity characteristics. (L) 5.1 cm-diameter steel pipe segments; (M) Ultra Mag flow meter with 5.1 cm-diameter inlet and outlet. (N) Adjustable gate valve for controlling flow rate. (O) 4.5 cm x 25.4 cm treated lumber used to mount the above-surface portion of the system. (P) Aluminum frame with 4-point connection that attaches to the on-boat hoist is not shown for clarity.
Figure 2.2: Photograph of the SOD Chamber
This photograph shows the SOD chamber with Plexiglas shell, stainless steel flange and stainless steel skirt that penetrates the sediment. The contraction / expansion sections are shown prior to the PVC pipes being attached. (This photograph shows parts A through E of the diagram on Figure 2-1). The aluminum frame (part P) not shown on Fig 2-1 for clarity, is also evident in this photo.

Figure 2.3: Photograph of the SOD Chamber
The board-mounted portion of the sampler while deployed in the field is shown; parts I through M of the diagram on Figure 2.1 are evident; along with the rubber fire hose (part H) hanging over the front of the boat.
Figure 2.4: Photograph of the SOD Chamber
A close-up showing the clear plastic pipe segment (part K) containing turbid water during operation at Bubbly Creek. The electric motor and centrifugal pump (part I) are also shown.

Figure 2.5: Photograph showing a large-scale view of the boat with SOD sampler deployed
A photograph of the field operations taken by USGS staff from the 35th Street bridge while the SOD sampler was deployed at Sample Station #4. The rubber hoses hanging over the front of the boat are evident. The vertical aluminum piping seen on both sides of the boat were driven into the sediment as anchors.
Figure 2.6: Photograph showing the Ponar dredge
The clamshell dredge in the open position as it is lowered to the streambed.
Chapter 3. Basis of \( SOD_{NR} \) Calculations\(^1 \)

The basic principle for \( SOD_{NR} \) calculation is that the sampling apparatus as a whole forms a control volume, and oxygen can only flux across the surface of the control volume through the exposed sediment surface at the base of the chamber. Mass balance for any constituent within a control volume is expressed by the following differential equation:

\[
\frac{dc}{dt} + \nabla \cdot F_{C,D} - \sum S_i = 0
\]  

(1)

where \( C \) denotes the concentration of the constituent of concern, in this case DO; \( t \) is time; \( \nabla \cdot F_{C,D} \) denotes the net convective and diffusive flux of the constituent across the boundary of the control volume; and \( \sum S_i \) represents the net internal rate of production of constituent by sources and sinks. For our sampler, the only terms present are the flux of oxygen out of the control volume through the area of exposed sediment and the oxygen sink associated with ambient water BOD,

\[
\nabla \cdot F_{C,D} = SOD_{NR} \left( \frac{A}{V} \right)
\]  

(2)

\[
\sum S_i = (\frac{dC_{DO}}{dt})_{amb}
\]  

(3)

where \( SOD_{NR} \) is the sediment oxygen demand under no resuspension conditions; \( A \) is the area of exposed sediment at the chamber base; \( V \) is the total volume of water contained in the sampling apparatus; and \( (\frac{dC_{DO}}{dt})_{amb} \) is the oxygen uptake rate associated with ambient water BOD. Substituting (2) and (3) into Eq. (1) gives

\[
SOD_{NR} = \left( \frac{V}{A} \right) \left[ (\frac{dC_{DO}}{dt})_{amb} - (\frac{dC_{DO}}{dt})_{TOTAL} \right]
\]  

(4)

where \( \frac{dC_{DO}}{dt} \) terms are negative when associated with oxygen consumption. \( SOD_{NR} \) is temperature-dependent, and it is customary to normalize field data sampled at different temperatures using an Arrhenius formulation for temperature correction (Chapra 1997):

\[\text{---------------------}\]

\(^1\) Work presented herein is included in the publication Waterman et al. (In press), posted ahead of print with permission from ASCE. The author acknowledges the contributions of the coauthors of that publication: Andrew R. Waratuke, Davide Motta, Yovanni A. Cataño-Lopera, Heng Zhang, and Marcelo H. García.
\[ SOD_{NR} = SOD_{NR20} \Theta_S^{(T-20)} \]  \hspace{1cm} (5)

where \( SOD_{NR20} \) is the sediment oxygen demand at 20°C; \( \Theta_S \) is a temperature correction coefficient with a typical value of 1.065 (Thomann and Mueller, 1987); and \( T \) is the water temperature (°C). \( \frac{dC_D}{dt} \) values are obtained from the measured oxygen drawdown curves, which past studies have found to be generally linear for non-resuspension conditions (Butts, 1974; Polls and Spielman, 1977). In Eq. (4), \( \frac{dC_D}{dt} \) \text{TOTAL} is the slope per linear regression of the portion of the curve that had reached a steady drawdown rate in the field. The \( \frac{dC_D}{dt} \) \text{amb} term is the slope of the oxygen drawdown curve in the ambient water, which was measured separately in the laboratory. Since the laboratory-measured values of \( \frac{dC_D}{dt} \) \text{amb} were typically not at the same temperature and DO concentration as the various in situ trials, it is necessary to correct them to match the field-measured conditions. A coefficient \( \chi \), representing the relative rate at which BOD is exerted for field conditions with respect to lab conditions is obtained by operating on a standard formulation for deoxygenation (Ambrose et al., 1988),

\[
\frac{dC_D}{dt} = K_D \Theta_D^{(T-20)} \left( \frac{C_D}{C_D + K_{BOD}} \right) C_{BOD} \]  \hspace{1cm} (6)

where \( K_D \) is the deoxygenation (oxidation) rate coefficient at 20 °C (day\(^{-1}\)); \( \Theta_D \) is a temperature correction coefficient, with a typical value of 1.047 (Phelps 1944); \( K_{BOD} \) is a half-saturation constant (mg/L), taken as 0.5 mg/L by Motta et al. (2010); and \( C_{BOD} \) is the BOD concentration (mg/L). The coefficient \( \chi \) is obtained by dividing Eq. (6) for field conditions by the value for laboratory conditions, under the assumption that \( K_D \) and \( C_{BOD} \) are the same between lab and field samples:

\[
\chi = \frac{\Theta_D^{(T-20)} \left( \frac{C_D}{C_D + K_{BOD}} \right)_{\text{FIELD}}}{\Theta_D^{(T-20)} \left( \frac{C_D}{C_D + K_{BOD}} \right)_{\text{LAB}}} \]  \hspace{1cm} (7)

\( \chi \) is then multiplied by \( \frac{dC_D}{dt} \) \text{amb} from the laboratory for input into Eq. (4).
Chapter 4. Computational Fluid Dynamics (CFD) Methods and Results

4.1 CFD Methods

The commercial non-hydrostatic finite-volume model FLOW-3D (Flow Science Inc., 2008) was utilized for the three-dimensional (3D) flow simulations of the experimental chamber. The model resolves fluid–fluid and fluid–air interfaces with a non-boundary-fitted rectangular grid and a volume of fluid (VOF) approach which resolves the grid cells into separate fractional fluid components containing the fraction of water and solid in the cell (Hirt and Nichols, 1981). Similarly, a fractional area-volume obstacle representation (FAVOR) approach is used to parameterize the flow within cells which contain fluid-obstacle boundaries (Hatton et al., 2007). The model solves the 3D Reynolds-averaged Navier–Stokes (RANS) equations for incompressible flow simultaneously with the continuity equation. For turbulence closure, FLOW-3D uses a RNG turbulence model (Yakhot and Smith, 1992) that is implemented in a very similar manner to the standard $k$-$\varepsilon$ closure for turbulent kinetic energy ($\bar{\varepsilon}$) and turbulent kinetic energy dissipation rate ($\varepsilon$) (Flow Science Inc., 2008). The RNG-based models rely less on empirical constants while setting a framework for the derivation of a range of models at different scales (Flow Science Inc., 2008).

Implementing the FLOW-3D model of the experimental chamber required a compromise between block-mesh-cell size and computational time needed to attain representative hydrodynamic results. Resolving both main flow and turbulent characteristics with accuracy requires using small computational cells, thus demanding significant computational time due to the size of the structures modeled. An initial simulation was run with cubic cells of dimensions $\Delta x = \Delta y = \Delta z = 2.0$ cm for a sufficient duration to reach steadiness of the flow discharge and associated statistical quantities such as mean kinetic energy and average turbulent kinetic energy. A second run was conducted with a smaller cell size of dimensions $\Delta x = \Delta y = \Delta z = 0.5$ cm. The flow discharges through the SOD chamber for the two cell sizes differed by small

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1 Work presented herein is included in the publication Waterman et al. (In press), posted ahead of print with permission from ASCE. The author acknowledges the contributions of the coauthors of that publication: Andrew R. Waratuke, Davide Motta, Yovanni A. Cataño-Lopera, Heng Zhang, and Marcelo H. García.
quantities. The finer mesh was finally chosen for the simulations since it provided adequate resolution for the mean and turbulent flow characteristics such as flow velocity, $k$, $\varepsilon$, and $u^*$. A 3D representation of the chamber of the U of I Hydrodynamic SOD Sampler is shown in Figure 4.1. The mesh block distribution used in FLOW-3D model is presented in Figure 4.2.

4.2 CFD Results

CFD simulations were performed for the full range of flow rates and sediment types identified during the field experiments. Sediment characteristics were obtained from particle size distributions presented in the previous CDM (2005) study of Bubbly Creek, and were qualitatively confirmed as described below in Section 5.1.1. Simulations were run with median sediment particle diameter $D_{50} = 30 \mu m$ (sediment class 1), $D_{50} = 125 \mu m$ (sediment class 2), and $D_{50} = 250 \mu m$ (sediment class 3). Roughness height $k_s$ in the simulations is estimated as $2.5D_{50}$. Simulated velocities for a 182 L/min representative flow rate with $D_{50} = 125 \mu m$ are shown in Figure 4.3. Shear velocity is related to the bed shear stress through the relationship $u^* = (\tau_b/\rho_w)^{0.5}$, where $\tau_b$ is bed shear stress and $\rho_w$ is fluid density. Spatial distribution of the resulting $u^*$-values for the representative flow rate are illustrated in Figure 4.4. The average $u^*$ is determined from the results of each CFD simulation by calculating the area-weighted average over the 0.147 m$^2$ exposed sediment area; all $u^*$-values are reported in Table 4.1, along with other hydrodynamic parameters for the range of experimental flow rates. The Reynolds number (Re) within the portion of the chamber with sediment exposed is calculated as $4R_h U/\nu$ where $U$ is the mean flow velocity and $R_h$ is the hydraulic radius (cross-sectional area divided by the wetted perimeter). The roughness Reynolds number (Re*) is defined as $u^*k_s/\nu$ where $k_s$ is the wall roughness height estimated, as mentioned, as $2.5D_{50}$. The results reveal hydraulically smooth turbulent flow (Re* < 3.5) through the chamber except for the highest flow rates in sandy sediment, where the flow is transitional. Tables 4.2 and 4.3 report the turbulence parameters for the chamber and the sampling system as a whole, respectively. Values of $k$ and $\varepsilon$ are reported according to their spatial distributions, where the subscripts “ave”, “5”, and “95” represent the average, the 5$^{th}$ percentile, and 95$^{th}$ percentile, respectively, of the distribution within the spatial domain. Within the chamber, $k$ and $\varepsilon$ are large at the inlet and decrease in
the downstream direction. Values are generally higher in the pipes and highest in the expansion/contraction sections.

4.3 Figures and Tables

**Figure 4.1:** Schematic diagram of SOD chamber used in CFD model
Figure prepared by Dr. Yovanni Cataño-Lopera.

**Figure 4.2:** Mesh block of SOD chamber used in CFD model
Figure prepared by Dr. Yovanni Cataño-Lopera.
Figure 4.3: 3-D rendering of the Horizontal Velocity $U$ (cm/s) using Flow-3D’s FAVOR

Velocity magnitudes computed by FLOW-3D within the modelled experimental chamber for a flow rate of 182 L/min and with sediment $D_{50}$ equal to 125 μm. The $D_{50}$ is the particle diameter of which 50% of the material comprising the sediment is finer. Figure prepared by Dr. Yovanni Cataño-Lopera.

Figure 4.4: Shear Velocity Distribution over Exposed Sediment in Chamber

Shear velocities ($u^*$) across the exposed sediment at the base of the sampling apparatus computed by FLOW-3D for the same simulation conditions shown in Figure 4.3. Figure prepared by Dr. Yovanni Cataño-Lopera.
Table 4.1: General Hydrodynamic Parameters within Portion of Chamber with Exposed Sediment

<table>
<thead>
<tr>
<th>$Q$ (L/min)</th>
<th>Re</th>
<th>$u^*$1 (cm/s)</th>
<th>$u^*$2 (cm/s)</th>
<th>$u^*$3 (cm/s)</th>
<th>Re*1</th>
<th>Re*2</th>
<th>Re*3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0</td>
<td>2677</td>
<td>0.128</td>
<td>0.129</td>
<td>0.135</td>
<td>0.10</td>
<td>0.40</td>
<td>0.84</td>
</tr>
<tr>
<td>60.8</td>
<td>6513</td>
<td>0.253</td>
<td>0.262</td>
<td>0.276</td>
<td>0.19</td>
<td>0.82</td>
<td>1.72</td>
</tr>
<tr>
<td>121.6</td>
<td>13026</td>
<td>0.481</td>
<td>0.503</td>
<td>0.519</td>
<td>0.36</td>
<td>1.57</td>
<td>3.24</td>
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<tr>
<td>182.4</td>
<td>19539</td>
<td>0.714</td>
<td>0.748</td>
<td>0.796</td>
<td>0.53</td>
<td>2.33</td>
<td>4.96</td>
</tr>
<tr>
<td>243.2</td>
<td>26052</td>
<td>0.932</td>
<td>1.014</td>
<td>1.054</td>
<td>0.70</td>
<td>3.16</td>
<td>6.57</td>
</tr>
</tbody>
</table>

Note: For $u^*$ and Re* values, the subscripts (1, 2, 3) represent the sediment class of the simulation.

Table 4.2: Turbulence Parameters within Portion of Chamber with Exposed Sediment

<table>
<thead>
<tr>
<th>$Q$ (L/min)</th>
<th>$k_{ave}$ (cm$^2$/s$^2$)</th>
<th>$k_5$ (cm$^2$/s$^2$)</th>
<th>$k_{95}$ (cm$^2$/s$^2$)</th>
<th>$\varepsilon_{ave}$ (cm$^2$/s$^3$)</th>
<th>$\varepsilon_5$ (cm$^2$/s$^3$)</th>
<th>$\varepsilon_{95}$ (cm$^2$/s$^3$)</th>
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</thead>
<tbody>
<tr>
<td>25.0</td>
<td>1.3</td>
<td>0.12</td>
<td>4.9</td>
<td>0.35</td>
<td>0.021</td>
<td>1.6</td>
</tr>
<tr>
<td>60.8</td>
<td>9.0</td>
<td>0.30</td>
<td>31.2</td>
<td>5.3</td>
<td>0.22</td>
<td>24.7</td>
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<td>121.6</td>
<td>39.1</td>
<td>1.0</td>
<td>132.4</td>
<td>45.2</td>
<td>1.5</td>
<td>207.9</td>
</tr>
<tr>
<td>182.4</td>
<td>89.4</td>
<td>2.0</td>
<td>295.3</td>
<td>152.7</td>
<td>4.2</td>
<td>689.7</td>
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<tr>
<td>243.2</td>
<td>162.2</td>
<td>3.3</td>
<td>528.6</td>
<td>367.2</td>
<td>9.1</td>
<td>1644.9</td>
</tr>
</tbody>
</table>

Note: All values are per simulation with sediment class 2.

Table 4.3. Turbulence Parameters within Entire Sampling System (excluding pump)

<table>
<thead>
<tr>
<th>$Q$ (L/min)</th>
<th>$k_{ave}$ (cm$^2$/s$^2$)</th>
<th>$k_5$ (cm$^2$/s$^2$)</th>
<th>$k_{95}$ (cm$^2$/s$^2$)</th>
<th>$\varepsilon_{ave}$ (cm$^2$/s$^3$)</th>
<th>$\varepsilon_5$ (cm$^2$/s$^3$)</th>
<th>$\varepsilon_{95}$ (cm$^2$/s$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0</td>
<td>2.4</td>
<td>0.15</td>
<td>9.1</td>
<td>2.1</td>
<td>0.022</td>
<td>11.8</td>
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<tr>
<td>60.8</td>
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<td>0.48</td>
<td>63.4</td>
<td>30.8</td>
<td>0.28</td>
<td>157.4</td>
</tr>
<tr>
<td>121.6</td>
<td>64.3</td>
<td>1.6</td>
<td>263.0</td>
<td>231.2</td>
<td>2.2</td>
<td>1129.3</td>
</tr>
<tr>
<td>182.4</td>
<td>132.3</td>
<td>3.2</td>
<td>515.2</td>
<td>632.0</td>
<td>7.4</td>
<td>3067.5</td>
</tr>
<tr>
<td>243.2</td>
<td>235.1</td>
<td>5.4</td>
<td>914.3</td>
<td>1450.8</td>
<td>17.1</td>
<td>6983.5</td>
</tr>
</tbody>
</table>

Note: All values are per simulation with sediment class 2.
Chapter 5.  Experimental Results

5.1 General Field Observations

Field data was collected with the U of I Hydrodynamic SOD Sampler on August 10-12 and September 8-9, 2009. The locations of the sample stations are shown in Figure 5.1, and the latitude-longitude of the stations are shown in Table 5.1. The most recent CSO events prior to the two sampling periods occurred respectively on July 11 and August 28, 2009.

5.1.1 Surface Sediment Characterization

The surface sediment characteristics were found to be highly variable, generally transitioning from coarse-grained to fine-grained in the downstream direction. This variability had a major influence on the onset and magnitude of sediment resuspension during the field sampling. A reconnaissance was subsequently undertaken on October 1, 2009 to map general texture types at the sediment surface by collecting 28 samples with the Ponar dredge and analyzing qualitatively per the field method of texture determination (Thien, 1979). Figure 5.2 shows a conceptual map of sediment conditions, along with all the data locations on which the map was derived. In the case of the fine-grained organic muck sediment, a distinction was also made between those located in “shallow” water and those located in “deep” water, as the resuspension characteristics appeared to differ based on the depth of the overlying water. The criterion used for the distinction was the bathymetric elevation -2.5 meters relative to the City of Chicago Datum. (This corresponds to a normal water depth of approximately 1.75 meters.)

Figure 5.2 was based primarily on the findings of the Ponar dredge sampling. It has been described as conceptual for a number of reasons. First, this study was not intended as a detailed delineation of sediment types; and a detailed delineation would obviously not consist of areas bounded by straight lines. Secondly, all samples did not match exactly with the mapped classification; this is particularly true near the banks where the sediment composition

\[ \text{Work presented herein is included in the publication Waterman et al. (In press), posted ahead of print with permission from ASCE. The author acknowledges the contributions of the coauthors of that publication: Andrew R. Waratuke, Davide Motta, Yovanni A. Cataño-Lopera, Heng Zhang, and Marcelo H. García.} \]
was much more random than the conceptual figure would suggest. Thirdly, all surface sediment data identified conditions at a particular instant of time; and conditions are likely to change on a CSO event-by-event basis. The conceptual map is simply intended to illustrate the general trend of sediment characteristics observed. The trend described generally matches the findings from the core samples and Ponar grab samples in the USACE sediment study (CDM, 2005). Table 5.2 provides laboratory analysis of the nine sediment stations sampled with the Ponar dredge during SOD sampling; Table 5.3 summarizes the findings from all the sediment characterization data sets analyzed. In addition to the gradation from coarse- to fine-grained sediment, the data also reveals a general trend of increasing percentage of volatile total solid in the sediment in the downstream direction. The exception is at Sample Station 1, located near RAPS, whose primary outlets are on the east side of the structure into the southernmost tip of Bubbly Creek. The wide area north of the structure, which contains Sample Station 1, is effectively a low velocity backwater zone where suspended material tends to deposit.

Figure 5.3 shows a profile along the length of Bubbly Creek with the various sediment properties included in Table 5.3. Stationing is per the previous plan view figures. There are some anomalies evident in Figure 5.3. The most evident is in the vicinity of Station 10+00 at the gravel loading / unloading facility (barge dock). The Ponar sample collected at sample station H revealed angular rock up to 10 cm in diameter, along with high percentages of coarse sand. Sample B06 from the USACE study showed similar results; for that sample, gravel comprised approximately 40% of the sediment volume; with a D₅₀ of 2800 μm. It is evident that this is the result of spillage associated with the gravel operation on the east bank. It is also evident from Figure 5.3 that at each location where the USACE collected and analyzed a Ponar grab sample, the sediment had considerably higher D₅₀ and percentage sand, and generally had lower percentage organic material, relative to the sediment deeper below the surface sampled by coring. It is possible that this is an anomaly due to a specific flow event preceding the sampling; or the result of unrepresentative sample locations or the inherent difficulty in getting a representative sample from a Ponar dredge. Regardless of the nature of this anomaly, it highlights the fact that Ponar sediment samples represent only a small area of the sediment surface at a particular instant in time.
5.1.2 Phases of Sediment Resuspension

Another significant finding was that sediment resuspension occurred in relatively distinct phases rather than as a simple increase in TSS concentration with increasing bed shear stress. The separate phases of resuspension are referred to as follows: (1) No Resuspension Phase; (2) Flaking Phase; (3A) Full Resuspension Phase; and (3B) Bedload Partitioning Phase. The classification into phases was used while recording the data and served as a useful guide during sampling. In the No Resuspension Phase, the water was basically clear with the only suspended sediments being the amount present in the ambient water. In the Flaking Phase, small-to moderate-size flakes of organic material (~5 to 20 mm diameter; ~1 mm thick) were scoured off the sediment surface, but had little influence on water color or opacity, until the flakes were eventually ground up in the pump impeller after a few passes. Flakes were generally observed to be put into suspension at the beginning of the trial, and then their concentration remained constant for the remainder of the trial while the flow rate was kept constant; when the flow rate was increased to the next level, new flakes were scoured. In fine-grained organic sediment, the Flaking Phase transitioned abruptly to the Full Resuspension Phase. In this latter phase, the water turned dark and almost entirely opaque; the oxygen drawdown rate increased substantially above that recorded during the Flaking Phase; and the water samples were commonly very thick with suspended sediment. In areas where the sediment contained a high percentage of sand, the Flaking Phase transitioned to the Bedload Partitioning Phase rather than Full Resuspension Phase. In such case, following the Flaking Phase, fairly high concentrations of fine sediment began to be resuspended. However, the TSS concentration and oxygen drawdown rate were considerably lower than in the Full Resuspension Phase that occurred in fine-grained sediment. Later analysis of VSS also revealed that the material in suspension had a significantly higher percentage of organic content than the sediment as a whole as represented by the respective Ponar dredge sample. Therefore it is speculated that the mobilized portion of the sediment was partitioned into the sandy fraction that saltated along the bed, and the fine-grained and organic fraction that was directly entrained into suspension. An example of the different phases of resuspension observed in the field is shown
in Figure 5.4. The resuspension phase for all experimental trials is provided in Table 5.4. In this table, \( u^* \) is interpolated from the CFD results of Table 4.1.

## 5.1.3 Miscellaneous Observations

- Algae had a significant influence on DO concentrations in the water column.

  During sampling performed during the morning hours in August, DO concentrations of approximately 2.0 mg/L were observed with little variation between the water surface and near the streambed (<0.5 mg/L). Over the course of the day, the DO steadily rose, reaching a concentration as high as 6.6 mg/L near the surface. The afternoon DO concentrations typically showed a substantial variation between the surface and the streambed - approximately 1.5 to 2.0 mg/L. During the September sampling, this phenomenon was also pronounced, but with starting DO concentrations at a higher value, approximately 4.5 mg/L; and with concentrations rising to approximately 9.0 mg/L at the surface in the afternoon.

  Further proof of the algae influence was obtained on the morning of 8/12/09 at 8:45 am (CDT). A longitudinal boat run was made along the approximate centerline of Bubbly Creek with the DO probe strapped onto the Echo Sounder mount 39 cm (15.25 in) beneath the water surface. Although the DO was low due to the morning hour, whenever a shady location (bridge, building on the east bank, etc.) was crossed the DO would drop substantially; and upon returning to the sun, the DO would rise by >1 mg/L.

- When comparing two SOD sample stations with fine-grained sediment texture, the sediment that was under deeper water was more resistant to resuspension than the sediment under shallow water.

  Sample Station 5 was characteristic of this phenomenon. The sediment was a highly organic muck, similar to that observed elsewhere along lower Bubbly Creek; but the major phase of resuspension was not initiated until the flow rate in the SOD sampler was increased to 172 L/min. In the shallower areas of muck, the major phase of resuspension was reached at flow rates less than 120 L/min.
Acceptable results from the DO probe were obtained even when velocity in the experimental chamber was less than 0.5 ft/sec.

As indicated in Section 2.2, the Clark-type DO probe utilized in this study (YSI Professional Plus) specified a minimum velocity of 0.5 ft/sec to prevent downward drift of DO readings. The reason for this specification is that the probe uses oxygen as part of its measurement procedure; and as a result a local zone of low DO can be produced around the probe yielding a non-representative DO measurement. During field measurements, caution was taken to not lower velocities excessively. For the trials involving lower flow rates, downward drift was observed, which yielded oscillations of the DO drawdown curves due to the following mechanism: the probe utilized oxygen, drawing down oxygen levels near the probe; as new water then entered the near-probe area due to advection, oxygen levels rose again, with the process then repeating. Oscillations were almost unnoticeably small for the high flow rates, but reached amplitudes of approximately 0.5 mg/L for the lowest flow rates (Trials 3A, 4A, 5A, 6A). The oscillations would introduce unacceptable error if the recording interval was sparse and/or the net DO drawdown over the course of the entire trial was low (less than the magnitude of the oscillations), because readings taken at random intervals along the oscillations would yield a noisy result that may not have a discernible drawdown pattern. However, in the current study measurements were recorded at 1 second intervals, which allowed capture of the full oscillatory pattern and the net oxygen drawdown in the control volume. The decision was made to not lower flow rates below 25 L/min due to the concern that the amplitude of the oscillations might overwhelm the total oxygen drawdown over the course of the test. The full range of flow rates measured during field trials was 25 L/min (0.0147 ft³/sec) to 224 L/min (0.1318 ft³/sec). The cross-sectional area of the chamber was 0.0229 m² (0.246 ft²). This yields a mean velocity in the longitudinal direction of the chamber that varies linearly between 0.060 ft/sec to 0.536 ft/sec for the full range of flow rates sampled.
5.2 Oxygen Demand Associated with No Resuspension Conditions (SOD\textsubscript{NR})

Only four field trials were achieved where sediment was not resuspended. A typical DO drawdown curve for non-resuspension conditions is provided as Figure 5.5, and all DO drawdown curves from the field experiments are provided in Appendix B. The four trials with no resuspension are Trials 2A, 3A, 4A and 6A. The oscillations in the drawdown curves are due to localized oxygen consumption by the polarographic probe which was manifested for relatively low flow velocity; higher velocities decreased the amplitude of oscillations. SOD\textsubscript{NR} is calculated using Eq. (4), with \((dC_{DO}/dt)\text{TOTAL}\) determined from linear regression of the drawdown curves, and \((dC_{DO}/dt)\text{amb}\) measured separately in the laboratory using field-collected water samples. SOD\textsubscript{NR20} is the temperature-normalized value calculated with Eq. (5). Resulting values of SOD\textsubscript{NR20} are between 6.7 and 12.1 g/m\textsuperscript{2}/day, and a summary of the data for the non-resuspension trials is provided in Table 5.5.

With the limited data obtained for non-resuspension conditions, a relationship between SOD\textsubscript{NR} and \(u^*\) could not be established. The following limitations hindered the ability to acquire the necessary data:

1. The onset of resuspension (Flaking Phase) always occurred at very low flow rates.
2. Using the Clark-type stirring-dependent DO probe, there was a minimum flow rate that could be set and still obtain viable DO drawdown data.
3. DO in the stream was generally low, which limited the number of experimental trials that could be performed at each setup.
5.3 Oxygen Demand Resulting from Sediment Resuspension (SODᵣ)

The DO drawdown curves for resuspension conditions are nonlinear, as opposed to the linear curves measured for no resuspension conditions. A typical curve is provided as Figure 5.6. All curves from the field experiments are provided in Appendix B, and with the exception of Trials 2A, 3A, 4A and 6A, each of the experiments involved some degree of resuspension. The characteristic non-linear shape is most evident in the trials with high flow rate and high suspended sediment concentration. Note that although the nonlinearity is most pronounced in the low $C_{DO}$ range, the value of $(dC_{DO}/dt)$ decreases throughout the course of the resuspension experiments. Table 5.6 reports $(dC_{DO}/dt)$ at its maximum value and where the curve passes through $C_{DO} = 2$ mg/L.

5.4 Relationship between Bed Shear Stress and Suspended Sediment Concentration

5.4.1 Critical Shear Velocity for Flaking Phase Resuspension

Shear velocities were assigned to each field trial using linear interpolation between points from Table 4.1. All data of suspended sediment concentration with associated shear velocities are reported in Table 5.7. It was evident that the threshold for Flaking Phase resuspension was similar regardless of sediment type or location in the channel. This is likely due to the flakes consisting of a shallow layer of organic debris (dead algae, detritus, biofilm growing on the sediment surface, recent unconsolidated deposition of CSO organics, etc.), whose resuspension behavior does not depend strongly on the texture of the sediment on which it overlies. Field methods and conditions did not allow identification of a precise shear velocity value under which Flaking Phase resuspension was initiated at each sample station. For each sample station, the lower boundary $u_{LB}$ is the highest shear velocity where no resuspension occurred, and the upper boundary $u_{UB}$ is the lowest shear velocity where resuspension was observed (Figure 5.7). A weighted mean $u_{crit}$ across all sample stations is calculated as

$$u_{crit} = \frac{\sum_{i=1}^{n} (u_{mix,i})(1/\Delta u_{*i})}{\sum_{i=1}^{n} (1/\Delta u_{*i})}$$

(8)
where \( \Delta u^* = u^*_{UB} - u^*_{LB} \) and \( u^*_{mid} = u^*_{LB} + (\Delta u^*/2) \). The weighting function \( 1/\Delta u^* \) assigns a higher weight to those sample stations where initiation of resuspension occurred within a narrower range and whose values are therefore presumably more accurate. Using Eq. (8), the mean critical shear velocity is 0.17 cm/sec, as also shown in Figure 5.7.

5.4.2 Critical Shear Velocities for Full Resuspension and Bedload Partitioning Phases

The observations recorded in the field notes in conjunction with the maximum slope of the oxygen drawdown curves led to the conclusion that TSS concentrations up to approximately 800 mg/L constituted Flaking phase resuspension in fine-grained sediment; and TSS concentrations up to approximately 300 mg/L constituted Flaking phase resuspension in sandy sediment. TSS exceeding those values constituted the subsequent phase (Full Resuspension or Bedload Partitioning). The transition to the Full Resuspension phase was typically abrupt; the transition to Bedload Partitioning was not clearly distinguishable in the field.

Sample Stations 1 and 3 were characterized by a fine-grained muck sediment and shallow surface water. At Sample Station 1, Trial 1C was observed to be very close to the threshold between Flaking and Full Resuspension, at a shear velocity of 0.381 cm/sec. At Sample Station 3, the threshold value lay between the shear velocity for Trial 3B (0.253 cm/sec) and Trial 3C (0.475 cm/sec). The critical shear velocity was established as 0.364 cm/sec, which is half-way between the shear velocity for Trials 3B and 3C. This is in the same vicinity as the value of 0.381 cm/sec estimated for Sample Station 1. This led to the conclusion that in the areas with fine-grained organic sediment and shallow water, the critical shear velocity to initiate Full Resuspension is approximately 0.37 cm/sec.

Sample Station 5 also had fine-grained muck sediment, but was in an area with deeper water than Sample Stations 1 and 3. At Station 5 the water in the sampling system gradually became more opaque as the flow rate was increased, although the oxygen drawdown changed little with each incremental change until Trial 5E was reached at shear velocity 0.686 cm/sec. The increase of shear velocity from 0.532 to 0.686 cm/sec at Trials 5D and 5E was accompanied by a dramatic increase in oxygen drawdown and TSS concentration. Initiation of Full Resuspension
was clearly between these two trials, and the transition was abrupt. The critical shear velocity was established as 0.61 cm/sec, half-way between the shear velocities of Trials 5D and 5E.

Sample Station 2 was in an area of fine sandy muck. The sediment sample “2SED” was approximately 10% organic (ie, the volatile fraction of the dried solids was 10% by weight); however, the mineral fraction of the sediment clearly had a higher percentage of sand than the sediment samples collected in the lower part of the stream. The coarser sediment composition altered the resuspension characteristics relative to the organic soils discussed above. Low flow rates were established for Trials 2A through 2D, and these trials were definitively in the Flaking phase. At Trial 2E, a threshold from light flaking to heavy flaking was recorded and consequently a sample was taken. The shear velocity for the trial was 0.589 cm/sec. It was possible that this constituted the critical shear stress where the sandy portion of the sediment started to be mobilized as bedload and the organic and fine-grained fraction of the sediment began partitioning into suspension. In other words, this was likely the initiation of the Bedload Partitioning phase. Trial 2F was clearly in the Full Resuspension phase, and the shear velocity was 0.930 cm/sec. The threshold for initiation of the Full Resuspension phase was established as 0.76 cm/sec, half-way between the shear velocity for Trials 2E and 2F.

At Sample Stations 4, 6, and 7 full resuspension was not achieved during the field experiments. These were located in areas whose sediment composition was dominated by sand, with Sample Station 4 consisting of a homogeneous fine-grained sand and Sample Stations 6 and 7 consisting of sand with larger grain size. Although the experimental apparatus was not able to achieve shear velocities high enough to experimentally determine the critical value in sandy sediment, for non-cohesive coarse-grained sediment, accurate theoretical and empirical relations have been formed through extensive studies in the past (Garcia, 2008). Evaluations regarding critical shear velocity for non-cohesive sediment without experimental data can be made with much more confidence relative to the entirely different set of equations used for cohesive soils. Using standard sediment transport relations allows the determination of critical shear velocity values for the coarse-grained reach of the stream.
The method for estimating critical shear velocity for sandy sediment was performed using the modified Shield’s diagram and Parker’s River Sedimentation Diagram (Garcia, 2008). The Shields’ diagram is a plot of the relation between the dimensionless particle Reynold’s Number ($\text{Re}_p$) and the dimensionless bed shear stress ($\tau^*$). The curves identify boundaries of the value $\tau^*$, above which material will be mobilized as either bedload or full resuspension. The variables graphed are calculated as follows:

$$\text{Re}_p = \frac{D_{50}}{v} \sqrt{\frac{gRD_{50}}{\rho}}$$  \hspace{1cm} (9)

where $g$ is the gravitational acceleration constant (9.81 m/sec$^2$) and $R$ is the submerged specific gravity of sediment grains, calculated as:

$$R = \frac{(\rho_s - \rho_w)}{\rho_w} \hspace{1cm} (10)$$

where $\rho_s$ is the density of the sediment and $\rho_w$ is the density of water.

$$\tau^* = \frac{\tau_B}{\rho gRD_{50}} \hspace{1cm} (11)$$

The value of $D_{50} = 0.250$ mm = 2.50x10$^{-4}$ m was taken from the USACE particle size distribution for Boring B11 (CDM, 2005). The value of $\rho_s$ was taken from the USACE geotechnical analysis of specific gravity for boring B11, which was 2.50 (CDM, 2005). The calculated value of $R$ is therefore 1.50. Using these values, the calculated value of $\text{Re}_p$ is 15.12. From the Shields’ Diagram (Garcia, 2008), the value for $\tau^*_c$ was found graphically to be 0.0225, where the subscript “c” indicates the critical value. $\tau_{BC}$ was then calculated from Eq. (11) to be 0.0826 N/m$^2$. The relation $u^* = \sqrt{\frac{\tau_B}{\rho}}$ is then used to yield $u^* = 0.0091$ m/sec or 0.91 cm/sec. This establishes the critical value of $u^*$ for which sand mobilization is initiated as bedload.

In a similar fashion, the value of $u^*$ for the transition from bedload (where the coarse material saltates along the bed of the stream) to full resuspension (where turbulence conveys material from near the bed into the overlying water column) can be found using Parker’s River Sedimentation Diagram (Garcia, 2008). The value for the dimensionless bed shear stress ($\tau^*_r$) was found graphically to be 0.175. Using the same calculations as above, the critical value for
transition into full suspension is \( u^* = 0.0254 \) m/sec or 2.54 cm/sec. All the critical values of shear velocity \( (u^*) \) are summarized in Table 5.8.

5.4.3 Shear Velocity and Suspended Sediment across all Phases

The critical shear velocities separating phases of resuspension are incorporated into plots relating shear velocity and suspended sediment concentration for each sample station, provided as Figures 5.8 through 5.13. Each of the curves was based on a relatively limited number of points. However, they do illustrate the general trend of organic fine-grained sediment entering into the Full Resuspension Phase with high concentrations of TSS at relatively low levels of bed shear stress; and as the sediment gets coarser (higher percentage of sand), the TSS values still increase with bed shear stress, but at a much lower rate. Note the difference in the shear velocity required to achieve Full Resuspension between Sample Stations 3 and 5, whose soil textures and organic content were very similar; this appears to be due to increased sediment compaction at Sample Station 5, where water depth is greater.

5.5 Laboratory Results

5.5.1 Laboratory Oxygen Uptake Experiments

The ambient water oxygen uptake rate, \( (dC_{DO}/dt)_{amb} \) was found to be \( 7.294 \times 10^{-5} \) mg/L/sec at water temperature equal to 22.1°C. Using an Arrhenius formulation with \( \Theta_D \) equal to 1.047 yields a \( (dC_{DO}/dt)_{amb} \) value of \( 6.715 \times 10^{-5} \) mg/L/sec when normalized to 20°C.

The results of oxygen uptake rate associated with various suspended sediment concentrations are provided in Appendix C. This data set was not relied upon to develop the formulations for \( SOD_R \) in Chapter 6, so tables summarizing this data were not generated. Some observations from these experiments are as follows:

- During the oxygen uptake tests on sediment / water mixtures, there was a brief initial stage of rapid oxygen drawdown followed by a more steady oxygen drawdown at a reduced rate.
The initial rapid drawdown typically lasted from 30 to 120 seconds after the probe was inserted into the BOD bottle. This is evident from the drawdown curves for the laboratory experiments included in Appendix C. We speculate that this may be the result of rapid oxidation of dissolved components from the liquid fraction of the sediment. It is noted that in the process of sediment being entrained into suspension during actual resuspension conditions in Bubbly Creek, the rapid oxidation of constituents within the liquid fraction in the sediment may also occur.

- The oxygen uptake tests on sediment / water mixtures using a standard dissolved oxygen (DO) probe have an upper limit on the concentration of sediment that can be mixed.

For the highly organic sediments, mixtures in excess of 100,000 mg/L resulted in the oxygen drawing down so rapidly in the BOD bottle that an accurate measurement of DO versus time could not be achieved. Within one minute of saturating the mixture with oxygen, the DO was completely expended. (It took approximately 30 to 45 seconds to pour the mixture into the BOD bottle, insert the probe, and begin taking readings.) In order to take accurate measurements of oxygen uptake for the high concentration mixtures, a more sophisticated system that pumps oxygen into the system over time (such as a respirometer) would be required.

5.5.2 Grain Size Distribution and Settling Velocity

Experiments on fine-grained sediment samples using the LISST-ST were performed primarily to assist in quantifying parameters for future numerical modeling efforts. Tables summarizing the data were not generated, and the reader is referred to the raw data provided in Appendix D. The data reveals $D_{50}$ values between 20 and 50 μm, which generally confirms the grain-size distributions provided in the CDM (2005) study for the portions of the stream containing fine-grained sediment. Settling velocities were found to be very low, generally on the order of 0.001 cm/sec.
Figure 5.1: SOD Sample Stations
Figure 5.1 (cont.)
Figure 5.2: Surface Sediment Characterization Map


MATCH LINE

BARGE DOCK / GRAVEL FACILITY

LEGEND

FINE‐GRAINED ORGANIC MUCK (DEEP WATER)
FINE‐GRAINED ORGANIC MUCK (SHALLOW WATER)
FINE SANDY ORGANIC MUCK
FINE SAND
MEDIUM TO COARSE SAND
COARSE SANDY‐GRAVEL (ANGULAR ROCK)
NOTE: THIS ANOMALOUS SEDIMENT TYPE APPEARS TO BE SPILLAGE FROM BARGE UNLOADING AT GRAVEL FACILITY

SOD SAMPLE STATION (PONAR DREDGE SAMPLE COLLECTED)
PONAR DREDGE SAMPLE COLLECTED 09/09/09 – NOT ON SOD SAMPLE STATION
PONAR DREDGE SAMPLE COLLECTED ON 10/01/09 – NOT ON SOD SAMPLE STATION
US ARMY CORPS OF ENGINEERS PONAR DREDGE SAMPLE COLLECTED: APRIL 2004
US ARMY CORPS OF ENGINEERS CORE SAMPLE COLLECTED: APRIL 2004

LEGEND

FINE‐GRAINED ORGANIC MUCK
(DEEP WATER)
FINE‐GRAINED ORGANIC MUCK (SHALLOW WATER)
FINE SANDY ORGANIC MUCK
FINE SAND
MEDIUM TO COARSE SAND
COARSE SANDY GRAVEL (ANGULAR ROCK)

SOD SAMPLE STATION (PONAR DREDGE SAMPLE COLLECTED)
PONAR DREDGE SAMPLE COLLECTED 09/09/09 - NOT ON SOD SAMPLE STATION
PONAR DREDGE SAMPLE COLLECTED ON 10/01/09 - NOT ON SOD SAMPLE STATION
US ARMY CORPS OF ENGINEERS PONAR DREDGE SAMPLE COLLECTED: APRIL 2004
US ARMY CORPS OF ENGINEERS CORE SAMPLE COLLECTED: APRIL 2004

GRAPHICAL SCALE

0 75 150 225 300
IN METERS

Figure 5.2 (cont.)
Figure 5.3: Centerline Profile showing various physical parameters of sediment
Figure 5.4: A photograph showing the different phases of resuspension observed

This photograph was taken in the field which illustrates changing water conditions in the sampling system during the course of a set of trials. These samples were collected from Sample Station #4, where the sediment was coarse and found to be relatively resistant to resuspension. Sample 4AI was collected during the priming process which represents ambient water conditions (no resuspension) observed during the low flow rate trial. Upon increasing the flow rate, flakes of organic material were first seen at a flow rate of 50 L/min. Increasing the flow rate at approximately 15 L/min intervals through a number of trials, the water opacity changed very little until 140 L/min, at which point the flaking became much heavier and the water turned noticeably more opaque. Sample 4A2 was taken at the end of the 140 L/min trial, which appeared to be a threshold between light flaking and heavy flaking. The TSS of this sample was 148 mg/L. The flow rate was again increased at approximately 15 L/min intervals, and at each stage the water became progressively more opaque. Sample 4A3 was pulled at the end of the trial where the maximum flow rate was 190 L/min. During sampling, it was presumed that the Full Resuspension phase had been achieved somewhere between 140 L/min and 190 L/min, but later analysis of the oxygen demand and TSS concentrations revealed that Full Resuspension had not yet been reached. Sample 4A3 appears fairly dark, but the TSS was only 386 mg/L. Other sample stations had TSS as high as 10,500 mg/L.
Figure 5.5: Typical DO Drawdown Curve for Non-Resuspension Conditions: Trial 2A

Figure 5.6: Typical DO Drawdown Curve for Resuspension Conditions: Trial 1B
Figure 5.7: Analysis of critical shear velocity ($u_*$) for onset of Flaking Phase resuspension

![Graph showing analysis of critical shear velocity with stations 1 to 6/7 and calculations for onset of resuspension.]

Figure 5.8: Suspended Solids concentration versus Shear Velocity at Sample Station 1

Note that no water sample was collected for Trial 1A at $u_*$ = 0.198 cm/sec, which was noted to be in the heavy Flaking phase.
Figure 5.9: Suspended Solids concentration versus Shear Velocity at Sample Station 2
Note that identifying the limits of the Bedload Partitioning phase was not attempted. Trial 2E would be encompassed within that phase.

Figure 5.10: Suspended Solids concentration versus Shear Velocity at Sample Station 3
The lower limit of Bedload Partitioning was calculated using incipient sediment motion relations with $D_{50} = 250 \, \mu m$. 

**Figure 5.11: Suspended Solids concentration versus Shear Velocity at Sample Station 4**

The suspended solids concentration versus shear velocity at Sample Station 4 is shown in the graph. The lower limit of Bedload Partitioning was calculated using incipient sediment motion relations with $D_{50} = 250 \, \mu m$. 

**Figure 5.12: Suspended Solids concentration versus Shear Velocity at Sample Station 5**

The graph illustrates the suspended solids concentration versus shear velocity at Sample Station 5. The lower limit of Bedload Partitioning was calculated using incipient sediment motion relations with $D_{50} = 250 \, \mu m$. 

---

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Figure 5.13: Suspended Solids concentration versus Shear Velocity at Sample Stations 6 and 7
The lower limit of Bedload Partitioning was calculated using incipient sediment motion relations with $D_{50} = 250 \mu m$. 
### Table 5.1. SOD Sample Station Locations (Lat-Long)

<table>
<thead>
<tr>
<th>Sample Station ID</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.825775306252</td>
<td>-87.658164072243</td>
</tr>
<tr>
<td>2</td>
<td>41.834386499234</td>
<td>-87.660157924587</td>
</tr>
<tr>
<td>3</td>
<td>41.841494691139</td>
<td>-87.665187896068</td>
</tr>
<tr>
<td>4</td>
<td>41.830240980754</td>
<td>-87.657365864283</td>
</tr>
<tr>
<td>5</td>
<td>41.838379208304</td>
<td>-87.663757780676</td>
</tr>
<tr>
<td>6</td>
<td>41.827143516655</td>
<td>-87.657484333317</td>
</tr>
<tr>
<td>7</td>
<td>41.827245149988</td>
<td>-87.657475349984</td>
</tr>
</tbody>
</table>

### Table 5.2. Analysis of Ponar dredge surface-sediment samples

<table>
<thead>
<tr>
<th>Description</th>
<th>Total Solid by Weight (%)</th>
<th>Volatile Total Solid by Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Station 1</td>
<td>52.91</td>
<td>11.05</td>
</tr>
<tr>
<td>Sample Station 2</td>
<td>43.43</td>
<td>10.09</td>
</tr>
<tr>
<td>Sample Station 3</td>
<td>22.09</td>
<td>19.80</td>
</tr>
<tr>
<td>Sample Station 4</td>
<td>71.47</td>
<td>1.61</td>
</tr>
<tr>
<td>Sample Station 5</td>
<td>32.05</td>
<td>18.71</td>
</tr>
<tr>
<td>Sample Station 6</td>
<td>72.46</td>
<td>3.36</td>
</tr>
<tr>
<td>Sample Station 7</td>
<td>69.83</td>
<td>3.17</td>
</tr>
<tr>
<td>7-XLEFT</td>
<td>63.17</td>
<td>5.58</td>
</tr>
<tr>
<td>7-XRIGHT</td>
<td>73.49</td>
<td>0.62</td>
</tr>
<tr>
<td>8SED</td>
<td>74.65</td>
<td>0.64</td>
</tr>
<tr>
<td>9SED</td>
<td>69.12</td>
<td>1.97</td>
</tr>
</tbody>
</table>

**Note:** Volatile Total Solid by Weight represents the percentage of the dried solid that volatilized in an oven at 550°C.
Table 5.3. Textures of Ponar sediment samples per field method

<table>
<thead>
<tr>
<th>Sample ID *</th>
<th>Field Notes (Texture)</th>
<th>Nearest Corps sample</th>
<th>$D_{50}$ (μm)</th>
<th>% Sand</th>
<th>% Organic (%VTSW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Muck with various household debris</td>
<td>B12</td>
<td>45</td>
<td>33.7</td>
<td>11.0 [1SED]</td>
</tr>
<tr>
<td>B</td>
<td>Sand; moderate to coarse grit</td>
<td>B13</td>
<td>1250</td>
<td>79.6</td>
<td>5.4</td>
</tr>
<tr>
<td>C-XCEN</td>
<td>Coarse sand</td>
<td>B11</td>
<td>250</td>
<td>88.6</td>
<td>3.4 [6SED]/ 3.2 [7SED]</td>
</tr>
<tr>
<td>C-XLEFT</td>
<td>Sand; moderate to coarse grit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-XRIGHT</td>
<td>Fine sand; prominent muck component relative to C-XCEN and C-XLEFT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-XCEN</td>
<td>Fine sand; homogeneous grain-size</td>
<td>B11</td>
<td>250</td>
<td>88.6</td>
<td>0.6 [8SED]</td>
</tr>
<tr>
<td>D-XLEFT</td>
<td>Fine sand; prominent muck component</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-XRIGHT</td>
<td>Fine sand; moderate muck; less organic than D-XLEFT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-XCEN</td>
<td>Fine sand; homogeneous; light to moderate muck component</td>
<td>G05/ B10</td>
<td>205/ 98</td>
<td>95.3/ 59.8</td>
<td>1.6 [4SED]</td>
</tr>
<tr>
<td>E-XLEFT</td>
<td>Fine to moderate-grained sand with some fine gravel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-XRIGHT</td>
<td>Muck; completely unconsolidated; slurry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-XCEN</td>
<td>Mucky fine sand; sand component homogeneous</td>
<td>B08</td>
<td>90</td>
<td>54.4</td>
<td>2.0 [9SED]</td>
</tr>
<tr>
<td>F-XLEFT</td>
<td>Muck; minimal fine sand component</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-XRIGHT</td>
<td>Mucky coarse sand; lots of fine gravel 3-8mm diam.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G-XCEN</td>
<td>Mucky fine sand; sand component homogeneous; very fine-grained</td>
<td>G03/ B07</td>
<td>105/ 30</td>
<td>86.0/ 25.5</td>
<td>10.1 [2SED]</td>
</tr>
<tr>
<td>G-XLEFT</td>
<td>Muck; cohesive; minimal fine sand component</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G-XRIGHT</td>
<td>Fine sandy muck; cohesive</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Coarse sandy gravel; angular rock up to 10 cm diam; very little organic</td>
<td>B06</td>
<td>2800</td>
<td>43.2</td>
<td>11</td>
</tr>
<tr>
<td>I-XCEN</td>
<td>Muck; cohesive; minimal sand</td>
<td>G02/ B05</td>
<td>100/ 40</td>
<td>67.2/ 23.3</td>
<td>14/ 12</td>
</tr>
<tr>
<td>I-XLEFT</td>
<td>Muck; cohesive; minimal sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-XRIGHT</td>
<td>Mucky coarse sand; non-cohesive; with fine gravel 3mm diam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J-XCEN</td>
<td>Muck; much undecomposed organic debris (twigs, leaves, etc.); light to moderate amount of coarse sand and fine gravel</td>
<td>G02/ B05</td>
<td>100/ 40</td>
<td>67.2/ 23.3</td>
<td>18.7 [5SED]</td>
</tr>
<tr>
<td>K-XCEN</td>
<td>Fine sandy muck</td>
<td>G01/ B03</td>
<td>125/ 21</td>
<td>19.9</td>
<td>10/ 26</td>
</tr>
<tr>
<td>L-XCEN</td>
<td>Muck; loose, greasy, non-cohesive; no discernible sand component</td>
<td>B02</td>
<td>28</td>
<td>16.7</td>
<td>19.8 [3SED]</td>
</tr>
<tr>
<td>L-XLEFT</td>
<td>Muck; cohesive</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-XRIGHT</td>
<td>Muck; loose, greasy, non-cohesive</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M-XCEN</td>
<td>Muck; loose, greasy, non-cohesive</td>
<td>B01A</td>
<td>26</td>
<td>32.5</td>
<td>22</td>
</tr>
</tbody>
</table>

Notes for Table 5.3 are included on the following page
Table 5.3 (cont.)

Note *: The sample identification number given in the field was “PDS-“ followed by the ID shown in the table. The qualifying terms “XCEN”, “XLEFT”, and “XRIGHT” refer to the position on the stream cross section where the sample was taken at a given sample station. Left and right refer to the position as looking downstream; and XCEN refers to the center of the cross section.

Note 1: All cells with gray shading show results from the sediment analysis performed in the USACE study (CDM, 2005). The \( D_{50} \) is the sediment diameter from the particle size distribution where 50% of the material is finer than the given diameter. The % Organic (% Volatile Total Solid by Weight) column is the percent of the dried sample that volatilized after being heated per the methods outlined in the above-referenced document. The % Sand column represents the percent of the total weight of the sample after the organics were volatilized. The samples labeled Gxx were grab samples from the surface collected with a Ponar dredge. The samples labeled Bxx were core samples. The portion of the sediment core analyzed was typically a meter or more below the sediment surface.

Note 2: The orange cells show the % Volatile Total Solid by Weight from samples collected by U of I and analyzed by the MWRDGC analytical lab as part of the current study. These values were used rather than the results from the USACE study when near a Ponar sample location due to their more recent origin.
Table 5.4. Resuspension Phase for all Experimental Trials

<table>
<thead>
<tr>
<th>Trial ID</th>
<th>$Q$ (L/min)</th>
<th>Sediment Class</th>
<th>$u_*$ (cm/s)</th>
<th>Resuspension Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>45</td>
<td>1</td>
<td>0.198</td>
<td>Flaking (Heavy)</td>
</tr>
<tr>
<td>1B</td>
<td>215</td>
<td>1</td>
<td>0.831</td>
<td>Full</td>
</tr>
<tr>
<td>1C</td>
<td>95</td>
<td>1</td>
<td>0.381</td>
<td>Flaking (Heavy)</td>
</tr>
<tr>
<td>2A</td>
<td>59</td>
<td>2</td>
<td>0.255</td>
<td>Flaking (Light)</td>
</tr>
<tr>
<td>2B</td>
<td>82.5</td>
<td>2</td>
<td>0.348</td>
<td>Flaking</td>
</tr>
<tr>
<td>2C</td>
<td>100</td>
<td>2</td>
<td>0.417</td>
<td>Flaking</td>
</tr>
<tr>
<td>2D</td>
<td>123</td>
<td>2</td>
<td>0.509</td>
<td>Flaking</td>
</tr>
<tr>
<td>2E</td>
<td>143</td>
<td>2</td>
<td>0.589</td>
<td>Bedload Partitioning</td>
</tr>
<tr>
<td>2F</td>
<td>224</td>
<td>2</td>
<td>0.930</td>
<td>Full</td>
</tr>
<tr>
<td>3A</td>
<td>25</td>
<td>1</td>
<td>0.128</td>
<td>None</td>
</tr>
<tr>
<td>3B</td>
<td>60</td>
<td>1</td>
<td>0.253</td>
<td>Flaking</td>
</tr>
<tr>
<td>3C</td>
<td>120</td>
<td>1</td>
<td>0.475</td>
<td>Full</td>
</tr>
<tr>
<td>3D</td>
<td>199</td>
<td>1</td>
<td>0.774</td>
<td>Full</td>
</tr>
<tr>
<td>4A</td>
<td>26</td>
<td>3</td>
<td>0.139</td>
<td>None</td>
</tr>
<tr>
<td>4Ai</td>
<td>38</td>
<td>3</td>
<td>0.186</td>
<td>None</td>
</tr>
<tr>
<td>4Aii</td>
<td>51</td>
<td>3</td>
<td>0.237</td>
<td>Flaking</td>
</tr>
<tr>
<td>4Aiii</td>
<td>60</td>
<td>3</td>
<td>0.273</td>
<td>Flaking</td>
</tr>
<tr>
<td>4Av</td>
<td>72</td>
<td>3</td>
<td>0.321</td>
<td>Flaking</td>
</tr>
<tr>
<td>4Avi</td>
<td>86</td>
<td>3</td>
<td>0.377</td>
<td>Flaking</td>
</tr>
<tr>
<td>4Avii</td>
<td>109</td>
<td>3</td>
<td>0.469</td>
<td>Flaking</td>
</tr>
<tr>
<td>4Aviii</td>
<td>128</td>
<td>3</td>
<td>0.548</td>
<td>Flaking</td>
</tr>
<tr>
<td>4Aix</td>
<td>140</td>
<td>3</td>
<td>0.603</td>
<td>Flaking (Heavy)</td>
</tr>
<tr>
<td>4Ax</td>
<td>155</td>
<td>3</td>
<td>0.671</td>
<td>Flaking (Heavy)</td>
</tr>
<tr>
<td>4Axii</td>
<td>171</td>
<td>3</td>
<td>0.744</td>
<td>Flaking (Heavy)</td>
</tr>
<tr>
<td>4Axiii</td>
<td>190</td>
<td>3</td>
<td>0.828</td>
<td>Bedload Partitioning</td>
</tr>
<tr>
<td>4B</td>
<td>188</td>
<td>3</td>
<td>0.820</td>
<td>Bedload Partitioning</td>
</tr>
<tr>
<td>5A</td>
<td>30</td>
<td>1</td>
<td>0.145</td>
<td>Flaking</td>
</tr>
<tr>
<td>5B</td>
<td>62</td>
<td>1</td>
<td>0.258</td>
<td>Flaking</td>
</tr>
<tr>
<td>5C</td>
<td>101</td>
<td>1</td>
<td>0.404</td>
<td>Flaking</td>
</tr>
<tr>
<td>5D</td>
<td>135</td>
<td>1</td>
<td>0.532</td>
<td>Flaking</td>
</tr>
<tr>
<td>5E</td>
<td>175</td>
<td>1</td>
<td>0.686</td>
<td>Full</td>
</tr>
<tr>
<td>5F</td>
<td>200</td>
<td>1</td>
<td>0.777</td>
<td>Full</td>
</tr>
<tr>
<td>6A</td>
<td>30</td>
<td>3</td>
<td>0.155</td>
<td>None</td>
</tr>
<tr>
<td>6B</td>
<td>76</td>
<td>3</td>
<td>0.337</td>
<td>Flaking (Light)</td>
</tr>
<tr>
<td>6C</td>
<td>207</td>
<td>3</td>
<td>0.900</td>
<td>Flaking</td>
</tr>
<tr>
<td>7A</td>
<td>140</td>
<td>3</td>
<td>0.603</td>
<td>Flaking</td>
</tr>
<tr>
<td>7B</td>
<td>202.5</td>
<td>3</td>
<td>0.881</td>
<td>Flaking</td>
</tr>
</tbody>
</table>

§ The first number in the Trial ID is the sample station; the letter represents a specific trial at that station
Table 5.5. Summary of results for measurements involving no sediment resuspension

<table>
<thead>
<tr>
<th>Trial ID</th>
<th>Sediment Class</th>
<th>$u^*$ (cm/s)</th>
<th>$(dC_{DO}/dt)_\text{TOTAL}$ (mg/L/sec)</th>
<th>$T$ (°C)</th>
<th>$SOD_{NR20}$ (g/m²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A</td>
<td>2</td>
<td>0.255</td>
<td>$-4.19 \cdot 10^{-4}$</td>
<td>26.7</td>
<td>6.7</td>
</tr>
<tr>
<td>3A</td>
<td>1</td>
<td>0.128</td>
<td>$-7.47 \cdot 10^{-4}$</td>
<td>27.8</td>
<td>12.1</td>
</tr>
<tr>
<td>4A</td>
<td>3</td>
<td>0.139</td>
<td>$-3.93 \cdot 10^{-4}$</td>
<td>25.9</td>
<td>6.8</td>
</tr>
<tr>
<td>6A</td>
<td>3</td>
<td>0.155</td>
<td>$-4.76 \cdot 10^{-4}$</td>
<td>24.4</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Table 5.6. Summary of oxygen demand measurements for trials involving sediment resuspension

<table>
<thead>
<tr>
<th>Trial ID</th>
<th>Sediment Class</th>
<th>Resuspension Phase</th>
<th>TSS (mg/L)</th>
<th>$T$ (°C)</th>
<th>$(dC_{DO}/dt)_{\text{max}}$ (mg/L/sec)</th>
<th>$dC_{DO}/dt$ at $C_{DO}=2$mg/L (mg/L/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>1</td>
<td>Flaking (Heavy)</td>
<td>-</td>
<td>26.6</td>
<td>-0.00120</td>
<td>-0.00120</td>
</tr>
<tr>
<td>1B</td>
<td>1</td>
<td>Full</td>
<td>2984</td>
<td>26.5</td>
<td>-0.00821</td>
<td>-0.00517</td>
</tr>
<tr>
<td>1C</td>
<td>1</td>
<td>Flaking (Heavy)</td>
<td>582</td>
<td>28.2</td>
<td>-0.00243</td>
<td>-0.00146</td>
</tr>
<tr>
<td>2F</td>
<td>2</td>
<td>Full</td>
<td>3152</td>
<td>27.5</td>
<td>-0.00574</td>
<td>-0.00400</td>
</tr>
<tr>
<td>3B</td>
<td>1</td>
<td>Flaking</td>
<td>236</td>
<td>28.1</td>
<td>-0.00119</td>
<td>-0.00066</td>
</tr>
<tr>
<td>3C</td>
<td>1</td>
<td>Full</td>
<td>3440</td>
<td>28.2</td>
<td>-0.00861</td>
<td>-0.00861</td>
</tr>
<tr>
<td>4B</td>
<td>3</td>
<td>Bedload Partitioning</td>
<td>386</td>
<td>26.2</td>
<td>-0.00141</td>
<td>-0.00141</td>
</tr>
<tr>
<td>5A</td>
<td>1</td>
<td>Flaking</td>
<td>-</td>
<td>23.6</td>
<td>-0.00139</td>
<td>N/A</td>
</tr>
<tr>
<td>5B</td>
<td>1</td>
<td>Flaking</td>
<td>110</td>
<td>25.0</td>
<td>-0.00063</td>
<td>N/A</td>
</tr>
<tr>
<td>5C</td>
<td>1</td>
<td>Flaking</td>
<td>420</td>
<td>25.3</td>
<td>-0.00089</td>
<td>N/A</td>
</tr>
<tr>
<td>5D</td>
<td>1</td>
<td>Flaking</td>
<td>776</td>
<td>25.4</td>
<td>-0.00077</td>
<td>-0.00033</td>
</tr>
<tr>
<td>5E</td>
<td>1</td>
<td>Full</td>
<td>5392</td>
<td>25.1</td>
<td>-0.00859</td>
<td>-0.00859</td>
</tr>
<tr>
<td>6C</td>
<td>3</td>
<td>Flaking</td>
<td>252</td>
<td>23.9</td>
<td>-0.00111</td>
<td>-0.00111</td>
</tr>
<tr>
<td>7A</td>
<td>3</td>
<td>Flaking</td>
<td>79</td>
<td>24.8</td>
<td>-0.00097</td>
<td>N/A</td>
</tr>
<tr>
<td>7B</td>
<td>3</td>
<td>Flaking</td>
<td>166</td>
<td>24.5</td>
<td>-0.00121</td>
<td>-0.00121</td>
</tr>
</tbody>
</table>

Note: Gray-shaded cells were not included in the formulation of the $SOD_{t}$ term, because either TSS data was not obtained or the trial was ended before DO was allowed to draw down to 2.0 mg/L.
### Table 5.7. Summary of results for suspended sediment samples

<table>
<thead>
<tr>
<th>Trial ID</th>
<th>Class</th>
<th>$u^*$ (cm/s)</th>
<th>Resuspension Phase</th>
<th>TSS (mg/L)</th>
<th>VSS (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>1</td>
<td>0.831</td>
<td>Full</td>
<td>2984</td>
<td>984</td>
</tr>
<tr>
<td>1C</td>
<td>1</td>
<td>0.381</td>
<td>Flaking</td>
<td>582</td>
<td>218</td>
</tr>
<tr>
<td>2E</td>
<td>2</td>
<td>0.589</td>
<td>Bedload</td>
<td>434</td>
<td>152</td>
</tr>
<tr>
<td>2F</td>
<td>2</td>
<td>0.930</td>
<td>Full</td>
<td>3152</td>
<td>1004</td>
</tr>
<tr>
<td>3A</td>
<td>1</td>
<td>0.128</td>
<td>None</td>
<td>90</td>
<td>28</td>
</tr>
<tr>
<td>3B</td>
<td>1</td>
<td>0.253</td>
<td>Flaking</td>
<td>236</td>
<td>76</td>
</tr>
<tr>
<td>3C</td>
<td>1</td>
<td>0.475</td>
<td>Full</td>
<td>3440</td>
<td>940</td>
</tr>
<tr>
<td>3D</td>
<td>1</td>
<td>0.774</td>
<td>Full</td>
<td>10528</td>
<td>2692</td>
</tr>
<tr>
<td>4A</td>
<td>3</td>
<td>0.603</td>
<td>Flaking</td>
<td>148</td>
<td>58</td>
</tr>
<tr>
<td>4B</td>
<td>3</td>
<td>0.820</td>
<td>Bedload</td>
<td>386</td>
<td>148</td>
</tr>
<tr>
<td>5B</td>
<td>1</td>
<td>0.258</td>
<td>Flaking</td>
<td>110</td>
<td>40</td>
</tr>
<tr>
<td>5C</td>
<td>1</td>
<td>0.404</td>
<td>Flaking</td>
<td>420</td>
<td>148</td>
</tr>
<tr>
<td>5D</td>
<td>1</td>
<td>0.532</td>
<td>Flaking</td>
<td>776</td>
<td>224</td>
</tr>
<tr>
<td>5E</td>
<td>1</td>
<td>0.686</td>
<td>Full</td>
<td>5392</td>
<td>1420</td>
</tr>
<tr>
<td>5F</td>
<td>1</td>
<td>0.777</td>
<td>Full</td>
<td>5412</td>
<td>1436</td>
</tr>
<tr>
<td>6C</td>
<td>3</td>
<td>0.900</td>
<td>Flaking</td>
<td>252</td>
<td>140</td>
</tr>
<tr>
<td>7A</td>
<td>3</td>
<td>0.603</td>
<td>Flaking</td>
<td>79</td>
<td>46</td>
</tr>
<tr>
<td>7B</td>
<td>3</td>
<td>0.881</td>
<td>Flaking</td>
<td>166</td>
<td>88</td>
</tr>
</tbody>
</table>

### Table 5.8. Critical Shear Velocities

<table>
<thead>
<tr>
<th>Description of Phase Transition</th>
<th>Critical $u^*$ (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flaking Initiated regardless of sediment type</td>
<td>0.17</td>
</tr>
<tr>
<td>Fine-grained shallow organic sediment enters full resuspension</td>
<td>0.37</td>
</tr>
<tr>
<td>Fine-grained deep organic sediment enters full resuspension</td>
<td>0.61</td>
</tr>
<tr>
<td>Sandy muck enters full resuspension</td>
<td>0.76</td>
</tr>
<tr>
<td>Sandy sediment is mobilized as bedload; fine-grained and organic fraction is partitioned into the water column</td>
<td>0.91</td>
</tr>
<tr>
<td>Sandy sediment transitions from bedload to full suspension</td>
<td>2.54</td>
</tr>
</tbody>
</table>
Chapter 6. Analysis of Results

6.1 Analysis of $SOD_{NR}$

6.1.1 Comparison with Past Studies

Comparing the values of $SOD_{NR}$ obtained during this study with past Bubbly Creek studies, the 2007 study by MWRDGC obtained values of 1.38 g/m$^2$/day in the turning basin and 3.26 g/m$^2$/day along the east bank near 33$^{rd}$ Street (very near Sample Station 2 of the present study). Polls and Spielman (1977) obtained measurements of 3.42 and 4.42 g/m$^2$/day at the Archer Avenue bridge. The values found in the current study are uniformly higher than these previous measurements. There are a number of possible explanations for the differences:

(1) It is possible that the previous measurements were performed using sampling techniques with lower flow velocities; and that the difference between the $SOD_{NR}$ values represents velocity-dependent effects.

(2) $SOD_{NR}$ in this type of system is variable in time. The $SOD_{NR}$ is dependent on the recentness of the previous combined sewer overflow (CSO) events; the depositional or erosional characteristic of the recent events; and the amount and type of material deposited. The most recent event before the August 10-12, 2009 sampling was on July 11, 2009; and the most recent event before the September 8-9, 2009 sampling was on August 28, 2009. The timing and character of events that occurred prior to past sampling performed by the other agencies is unknown.

(3) The SOD measurements of the present study were taken under very warm water conditions that approached 30°C in some cases. The values were then normalized to a temperature of 20°C using standard temperature relationships established in previous research. The measurements of Polls and Spielman (1977) were taken at 20°C and 10°C; and it was not evident in the MWRDGC (2007) study when their measurements were

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1 Work presented herein is included in the publication Waterman et al. (In press), posted ahead of print with permission from ASCE. The author acknowledges the contributions of the coauthors of that publication: Andrew R. Waratuke, Davide Motta, Yovanni A. Cataño-Lopera, Heng Zhang, and Marcelo H. García.

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taken or at what temperature. It is possible that special conditions exist in Bubbly Creek that would warrant modifying the standard temperature relationship.

(4) For both the current and previous studies, the number of measurements has been limited. It is possible that if large numbers of measurements had been taken, statistical analysis would have resolved some of the variability in the data.

6.1.2 Decreased $SOD_{NR}$ under Low-Velocity or Low Ambient DO Conditions

As described in Section 1.2, past research has demonstrated that for non-resuspension conditions, the DO flux increases asymptotically toward a maximum value as flow velocity (or shear velocity) increases. For low velocity conditions, $SOD_{NR}$ is limited by the rate of diffusion through a thin diffusive sublayer at the sediment/water interface. With increasing velocity, the diffusive sublayer becomes thinner, and turbulent fluctuations deliver DO from the water column into the diffusive sublayer at a higher frequency. The asymptotic maximum is reached when DO is delivered through the diffusive sublayer at a sufficiently high rate such that biological and chemical oxygen consumption rates in the sediment limit further increases in the DO flux with increasing velocity.

In the current study, field measurements were taken under well-mixed conditions in the chamber and where ample ambient water DO (generally >2 mg/L) was present. It can be presumed that the measured $SOD_{NR}$ was near the asymptotic maximum described above. As a result, it can be expected that if conditions were fairly stagnant in Bubbly Creek or if ambient water DO content was very low, then $SOD_{NR}$ would be less than the field measured values. In the context of calculating the DO flux (i.e., $SOD_{NR}$) as being equal to $\beta \cdot \Delta C_{DO}$ per Boudreau and Guinasso (1982), low velocities would decrease $\beta$ relative to the field experiments; and low ambient water DO would reduce $\Delta C_{DO}$ relative to the field experiments.

The mass transfer coefficient $\beta$ is known to be linearly dependent with $u^*$ (see O’Connor et al., 2009 for a list of studies demonstrating that functional form). Therefore it is evident that if the values of $u^*$ resulting from prototype scale flows is less than that of the field experiments, then $SOD_{NR}$ will also be less than that measured during field experiments, assuming that $\Delta C_{DO}$ is the same between prototype and experiment. Another way to illustrate the assertion that $SOD_{NR}$
may be less than that measured experimentally is through an analytical framework described by Motta (2008). This analysis involves a hypothetical steady state condition in which the water column forms a control volume, and all oxygen entering the control volume by reaeration is consumed by $SOD_{NR}$; the net advection effect is zero, and $SOD_{NR}$ and reaeration are the only sources/sinks of DO in the simplified system. Equating sediment oxygen demand to the reaeration rate can be performed using the following relations:

$$SOD_{NR} = \beta \cdot \Delta C_{DO} \quad (12)$$

where $\beta$ has units [L/T] and $\Delta C_{DO}$ has units [M/L³]. Given the linear relationship between $\beta$ and $u^*$, a simplified form can therefore be stipulated as

$$\beta = K_1 u^* \quad (13)$$

where $K_1$ is an empirical constant which can be calculated from the field data. The value of the concentration difference across the diffusive sublayer, $\Delta C_{DO}$, is

$$\Delta C_{DO} = C_{DO,bulk} - C_{DO,sub} \quad (14)$$

where $C_{DO,bulk}$ is the bulk water column DO concentration and $C_{DO,sub}$ is the subsurface pore water DO concentration at the interface. Past experiments performed with DO microelectrodes have demonstrated that $C_{DO,sub}$ is generally very low (e.g., Gunderson and Jorgensen, 1990), and for this simplified analysis it can be assumed to be 0. This assumption only holds for water-side controlled conditions where all DO delivered through the diffusive sublayer is rapidly consumed in the sediment. Under these assumptions $\Delta C_{DO}$ can be considered to be equivalent to $C_{DO,bulk}$, which is the measured value of $C_{DO}$ from the field experiments. Reformulating Eq. (12) as

$$SOD_{NR} = (K_1 u^*)C_{DO} \quad (15)$$

each of the variables is known except $K_1$, which can then be calculated from each of the non-resuspension field trials shown in Table 5.5. The mean value of $K_1$ has been calculated from the field data as 0.027, which is held constant for the remainder of the analysis.
The following relates $u^*$ to the mean flow velocity $U$ on a reach-averaged basis:

$$u^* = \sqrt{C_f U}$$  \hspace{1cm} (16)$$

where $C_f$ is a friction coefficient, which can be expressed as:

$$C_f = \left[ \frac{1}{0.41} \ln \left( 11 \frac{H}{k_s} \right) \right]^{-2}$$  \hspace{1cm} (17)$$

where $H$ is the flow depth and $k_s$ is the roughness height, defined previously as a function of $D_{50}$. Using the mean depth of Bubbly Creek as 2.2 m, and a typical $D_{50}$ of 0.125 mm (.000125 m), a typical value of $C_f$ is calculated as 0.00113, which is held constant for the remainder of the analysis. Eq. (15) can consequently be reformulated as:

$$SOD_{NR} = (K_1 \sqrt{C_f U}) C_{DO}$$  \hspace{1cm} (18)$$

The surface sink $SOD_{NR}$ can be expressed as a volumetric sink to enumerate its impact on water column concentrations according to the following:

$$\left( \frac{dC_{DO}}{dt} \right) = \frac{SOD_{NR}}{H} = \left( K_1 \sqrt{C_f U} \right) C_{DO}$$  \hspace{1cm} (19)$$

(Note that with $U$ and $C_{DO}$ in units of m/s and mg/L, respectively, $SOD_{NR}$ will be in units of g/m$^2$/s.) The surface reaeration rate is quantified using the following equation:

$$\left( \frac{dC_{DO}}{dt} \right) = K_A \Theta^{-20} (C_{DO,sat} - C_{DO})$$  \hspace{1cm} (20)$$

where $K_A$ is the reaeration rate coefficient, $\Theta$ is the temperature correction factor, and $C_{DO,sat}$ is the saturation DO concentration. $K_A$ in this scenario is dictated solely by flow velocity and flow depth of the water column per the following equation:

$$K_A = \frac{3.93 (U^2)}{H^2}$$  \hspace{1cm} (21)$$

With this empirical relation, $K_A$, $U$, and $H$ are in units of day$^{-1}$, m/s, and m, respectively; therefore the reaeration source term is in units g/m$^3$/day. The balance between reaeration and
SOD can be expressed by setting the right side of Eq. 19 equal to the right side of Eq. 20, noting that unit conversion will be required to ensure the right hand side of the equation is in units of g/m³/day. Assuming that \( T = 20^\circ C \) and applying the necessary unit conversion factor, the balance between \( SOD_{NR} \) and reaeration rate becomes:

\[
\left( \frac{3.93(U^2)}{H^2} \right) \left( C_{DO, sat} - C_{DO} \right) = \frac{86400(K_i \sqrt{C_{DO}})C_{DO}}{H}
\]

(22)

where \( C_{DO, sat} = 9.23 \text{ mg/L at } 20^\circ C \). Treating \( U \) as a parameter to be varied, the only unknown is \( C_{DO} \). Once \( C_{DO} \) is calculated, the value of \( SOD_{NR} \) associated with that value of \( U \) can be calculated using Eq. (18). The results of a first-order sensitivity analysis is illustrated in Figure 6.1. The relation of \( SOD_{NR} \) as a function of \( U \) is illustrated in Figure 6.2, where the parameters \( K_i \), \( C_{D_{ini}} \), and \( C_{DO,sub} \) are varied individually from their reference conditions to determine the relative effects of these parameters on \( SOD_{NR} \) as formulated herein.

One key assumption of the formulation of Eq. (22) is that \( C_{DO, sub} \) equals 0, which is only true when the DO flux is water-side controlled; if the flux becomes sediment-side controlled because DO is delivered through the diffusive sublayer at a rate that exceeds consumption in the sediment, then a more sophisticated approach to model \( C_{DO,sub} \) would be required (e.g., Nakamura and Stefan, 1994). However this analysis is intended to illustrate how \( SOD_{NR} \) may be limited to values less than the field-measured values under low velocity conditions. It is also important to note that this analysis is hypothetical, and in reality, the mass balance within the control volume is more complex due to such factors as algae influence, wind effects at the surface, oxygen gradients due to diffusion and turbulence, etc.
6.2 Analysis of $SOD_R$

6.2.1 Formulation of Oxygen Sink Term associated with Resuspended Sediment

While $SOD_{NR}$ represents a DO sink per unit area, $SOD_R$ refers to unit volume. The hypothesis posed is that $SOD_R$ can be expressed in a fashion similar to first-order BOD kinetics with Monod term for DO; see Eq. (6). In order to express $SOD_R$ in that form and test the hypothesis, the four distinct components of the sink term are addressed: [1] a BOD concentration; [2] a temperature correction factor; [3] an oxygen-dependent term; and [4] a rate coefficient.

[1] $C_{BOD}$ is replaced with $C_{TSS}$ (concentration of TSS in mg/L). This substitution is made on the reasonable assumption that the amount of oxidizable material associated with organic-rich sediment in suspension is proportional to TSS. Over the small time frame of the field tests involving sediment resuspension, the amount of organic matter expended relative to the total can be assumed to be minimal, such that the evolution over time of the concentration of oxidizable material can be ignored after an equilibrium suspended sediment concentration is established in the chamber. For longer time intervals, the organic matter would be depleted to some degree, and Berg (1970) provides a framework for analyzing such depletion. Making the assumption that $C_{TSS}$ is directly proportional to $C_{BOD}$ implies also that dissolved organics and oxidizable inorganic constituents in the pore water released during sediment entrainment are proportional to $C_{TSS}$.

[2] The standard term for temperature dependence included in Eq. (6) is maintained, with $\Theta_D=1.047$, which is the commonly cited value for wastewater-derived BOD (Phelps 1944).

[3] The oxygen-dependent term in Eq. (6) is cast as Monod formulation ($C_{DO}/(C_{DO}+K_{BOD})$). In this analysis the half-saturation constant $K_{BOD}$ is replaced with a new half-saturation constant, $K_{BOD,TSS}$. Instantaneous slopes along the oxygen drawdown curves were calculated at various DO concentrations: 7.0, 6.0, 5.0, 4.0, 3.0, 2.0, 1.5, 1.0, 0.75, 0.50, and 0.25 mg/L. All the DO curves involving sediment resuspension pass through at least six of the given concentrations. The instantaneous slopes (i.e., the instantaneous oxygen uptake rates) were calculated by linear regression over a relatively short range encompassing the DO concentration of concern ±
0.5 mg/L for concentrations greater than 1.0 mg/L and ± 0.2 mg/L otherwise. The analysis of the instantaneous oxygen uptake rates was made under the assumption that the drawdown rate is dominated by the effect of the resuspended sediment (i.e., \( dC_{DO}/dt \approx SOD_R \)). This is reasonable, since the magnitude of \( dC_{DO}/dt \) associated with \( SOD_{NR} \) was found to be an order of magnitude less than that of \( dC_{DO}/dt \) for trials involving sediment resuspension (see Tables 5.5 and 5.6); moreover, \( dC_{DO}/dt \) associated with ambient water BOD was typically an order of magnitude less than the \( SOD_{NR} \) component. Observe also that the assumption to neglect \( SOD_{NR} \) in the mass balance is required because a measurement of \( SOD_{NR} \) had only been achieved for a portion of the sample stations.

For each drawdown curve, the oxygen uptake rates calculated along the curve were evaluated relative to the uptake rate calculated at \( C_{DO} = 2.0 \) mg/L. It is necessary to use this low DO concentration as the basis of comparison since most of the curves pass through, or close to, 2.0 mg/L; above that concentration, the amount of data is considerably reduced. Results are shown in Figure 6.3. As shown on the figure, three different formulations for the oxygen-dependent term are evaluated:

\[
\begin{align*}
(1) \text{ Monod formulation: } & \quad F(C_{DO}) = \frac{C_{DO}}{K_{BOD,TSS} + C_{DO}} \\
(2) \text{ Exponential formulation: } & \quad F(C_{DO}) = 1 - e^{-C_{DO} \cdot K_{BOD,TSS}} \\
(3) \text{ Second Order formulation: } & \quad F(C_{DO}) = \frac{C_{DO}^2}{K_{BOD,TSS} + C_{DO}^2}
\end{align*}
\]

The function \( F(C_{DO})/F(C_{DO} = 2) \) was evaluated statistically, yielding the value of \( K_{BOD,TSS} \) that provides the least root mean squared error (RMSE) for each of the three formulations. The Monod formulation provides the best fit, with \( K_{BOD,TSS} = 2.44 \) mg/L and RMSE = 0.1655. (The RMSE for the best fit of the exponential formulation is 0.1818 with \( K_{BOD,TSS} = 0.438 \) mg/L; and for the second-order formulation RMSE is 0.2625 with \( K_{BOD,TSS} = 2.186 \) mg/L.) Since the oxygen-dependent term is relative to \( C_{DO} = 2.0 \) mg/L, resulting values do not vary from 0 to 1 as in a standard Monod relation, but rather vary from 0 to some value larger than 1. The term takes the form \( F(C_{DO})/F(C_{DO} = 2 \text{ mg/L}) \) where \( F(C_{DO} = 2 \text{ mg/L}) \) is a constant equal to \((2/(2 + 2.44))\)
= 0.450; and \((1/F(C_{DO} = 2 \text{ mg/L})) = 2.22\). The value \(1/F(C_{DO} = 2)\) is hereafter referred to as \(\Lambda_2\).

The final form of the oxygen-dependent term is therefore:

\[
\Lambda_2 \left( \frac{C_{DO}}{C_{DO} + K_{BOD,TSS}} \right)
\]

where \(\Lambda_2 = 2.22\) and \(K_{BOD,TSS} = 2.44\) mg/L.

[4] \(K_{D,TSS2}\) is introduced as a substitute for the deoxygenation rate coefficient \(K_D\) in Eq. (6). \(K_{D,TSS2}\) is a constant of proportionality in the expression \(dC_{DO}/dt = K_{D,TSS2}C_{TSS}\) when evaluated at \(C_{DO} = 2.0\) mg/L and \(T = 20^\circ C\). Therefore, for this analysis all oxygen uptake rates were normalized to 20\(^\circ\)C; and only those drawdown curves that pass through \(C_{DO} = 2.0\) mg/L were considered. The results of the field data analysis are shown in Figure 6.4; and the results of the laboratory oxygen uptake analysis are shown in Figure 6.5. The slope on each figure is determined by linear regression, and is 0.0000778 [mg O\(_2\)/mg TSS/min] for the field data and 0.0000261 [mg O\(_2\)/mg TSS/min] for the laboratory data. These values are on the same order of magnitude, but the field data is considerably higher. This may be due to inherent differences in conditions under which the measurements were made, and the field data is regarded as more reliable. Since the slope of the \(dC_{DO}/dt\) versus \(C_{TSS}\) curve is the rate coefficient \(K_{D,TSS2}\), the result is \(K_{D,TSS2} = 0.0000778\) (mgO\(_2\)/mgTSS/min) or, equivalently, 0.112 (mgO\(_2\)/mgTSS/day).

Combining all four individual components into the new sink formulation therefore yields the following equation

\[
SOD_R = \left( K_{D,TSS2} \right) \left( \theta_D (T-20) \right) \left( \Lambda_2 \cdot \frac{C_{DO}}{(C_{DO}+K_{BOD,TSS})} \right) (C_{TSS})
\]

where \(SOD_R\) denotes \(dC_{DO}/dt\) in units of mg/L/day. The values for the coefficients are \(K_{D,TSS2} = 0.112\) mgO\(_2\)/mgTSS/day, \(\theta_D = 1.047\), \(\Lambda_2 = 2.22\), and \(K_{BOD,TSS} = 2.44\) mg/L.
6.2.2 Evaluation and Sensitivity Analysis of the Oxygen Sink Term associated with Resuspended Sediment

Equation (23) can be applied to the field data to verify that combining the four separate components accurately represents the observed drawdown curves. Using the field-measured $C_{TSS}$ and the initial $C_{DO}$, time evolution is simulated according to $C_{DO}(t + \Delta t) = C_{DO}(t) - SOD_R(t) \cdot \Delta t$. Figures 6.6 through 6.11 show the comparison between simulated and measured oxygen drawdown curves when using the reference values of $K_{D,TSS}$, $A_2$ and $K_{BOD,TSS}$ determined previously. The good fit of Eq. (23) to the data provides evidence to support the hypothesis that resuspended organic sediment can be treated as a surrogate of BOD. It is noted that the value of $K_{D,TSS} = 0.112$ [mg O$_2$/mg TSS/day] was derived from a linear regression to attempt to capture a general value, but it does not provide the best match to all the data sets. Where a better fit to the data could be obtained, a separate simulation using a separate value of $K_{D,TSS}$ is also included. In general, best fits of $K_{D,TSS}$ to individual trials yield values that range from 0.078 to 0.237 mgO$_2$/mgTSS/day. (In reality, $K_{D,TSS}$ does not likely vary between samples, but rather the relationship between $C_{BOD}$ and $C_{TSS}$ is different between different samples; this is addressed further in the Discussion.)

A sensitivity analysis of Eq. (23) was carried out by simulating DO time evolution with $T =$ 20°C, $C_{TSS} =$ 2000 mg/L, and initial $C_{DO} =$ 9.1 mg/L (saturation value at 20°C), and letting the DO concentration draw down to 0.5 mg/L; the values of the empirical constants $K_{D,TSS} =$ 0.112 mgO$_2$/mgTSS/day and $K_{BOD,TSS} =$ 2.44 mg/L were used as reference basis of comparison. Note that $A_2$ is a function of $K_{BOD,TSS}$; therefore $A_2$ is not independently varied in the analysis. The empirical constants were individually changed from their reference values within a reasonable range determined from the experiments. The time for $C_{DO}$ to drop from 9.1 mg/L to 0.5 mg/L for the reference values is denoted as $t_{ref}$, while the time for the same drop with the modified constant is $t_{mod}$. The dimensionless variable $\hat{t} = t_{mod}/t_{ref}$ was defined and the root mean square deviation (RMSD) was also calculated between the modified and reference drawdown curves. The results are provided in Table 6.1 and are illustrated in Figure 6.12. The simulations are fairly insensitive to variations in $K_{BOD,TSS}$; on the other hand, as expected, they are quite sensitive to variations in $K_{D,TSS}$. 

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6.3 Application of Critical Shear Velocities to Prototype Scale Flows

This section provides an example of how the findings of this report can be implemented in other models to simulate resuspension during actual stream flow events. As described previously, modeling the transport and fate of sediment put into suspension is beyond the scope of the current study, although such implementation in the future is practicable. The hydrodynamics portion of the 2D model STREMR-HySedWq was utilized by Motta (2008) to model a number of flow events in Bubbly Creek to determine the resultant shear velocities. Simulations for $Q = 2.19$ m$^3$/sec (50.0 million gallons per day (MGD)), $Q = 12$ m$^3$/sec (274.0 MGD) and $Q = 24$ m$^3$/sec (547.9 MGD) were performed. The spatially variable $u^*$ values calculated are compared to the critical values reported in Table 5.8 for the various sediment types present. Figures 6.13 to 6.15 illustrate the range of the resultant shear velocities and the associated resuspension phase achieved for each.

The figures reveal that $u^*$ values are uniformly higher in the shallow, broad, sandy reach of upper Bubbly Creek. During the 2.19 m$^3$/sec (50 MGD) event, no sediment in the stream enters the full resuspension phase, although Flaking is initiated in the high bed shear area in the upper stream. During a more substantial 12 m$^3$/sec (274.0 MGD) flow event, a large portion of the upper sandy streambed is mobilized as bedload, and the lower stream consists of a mosaic of areas that are in the Flaking and Full Resuspension phases. At this flow rate the entire streambed is in some form of resuspension. At a higher 24 m$^3$/sec (547.9 MGD) flow rate - which begins to approach the average flow rate of 37.8 m$^3$/sec (801.0 MGD) for a CSO event generated from RAPS - the entire upper sandy reach is mobilized as bedload, and some of the sand bed begins to transition from bedload into full suspension. Almost the entire portion of the lower stream is in full resuspension.
6.4 Figures

Figure 6.1: SOD_{NR} when limited by Flow Velocity under hypothetical steady state conditions

Figure 6.2: Sensitivity Analysis of Eq. (22) by varying parameters individually
Figure 6.3: Data analysis for the development of the oxygen-dependent component of the sink term for DO in presence of sediment resuspension.

Figure 6.4: Results of the analysis on field data to establish the rate coefficient, $K_{0,TSS2}$, according to the formulation $\frac{dC_{DO}}{dt} = K_{0,TSS2} C_{TSS}$. 

$Y = (7.78E-05) \times X$

$R^2 = 0.889$
Figure 6.5: Results of the analysis on laboratory data to establish the rate coefficient, $K_{O,TSS}$, according to the formulation $\frac{dC_{DO}}{dt} = K_{O,TSS} C_{TSS}$.

Figure 6.6: Simulation of Sink Term on Trial 1B
Figure 6.7: Simulation of Sink Term on Trial 1C

Field Data
Simulation 1: $K_{D,TSS2} = 0.112 \text{mgO}_2/\text{mgTSS/day}$
Simulation 2: $K_{D,TSS2} = 0.140 \text{mgO}_2/\text{mgTSS/day}$

Figure 6.8: Simulation of Sink Term on Trial 2F

Field Data
Simulation 1: $K_{D,TSS2} = 0.112 \text{mgO}_2/\text{mgTSS/day}$
Simulation 2: $K_{D,TSS2} = 0.078 \text{mgO}_2/\text{mgTSS/day}$
Figure 6.9: Simulation of Sink Term on Trial 3C

Figure 6.10: Simulation of Sink Term on Trial 4B
Figure 6.11: Simulation of Sink Term on Trial SE

Figure 6.12: Results of sensitivity analysis of Eq. (23) to the parameters $K_{D,TSS2}$ and $K_{BOD,TSS}$
Figure 6.13: Shear Velocities and Consequent Resuspension Phases for $Q=2.19$ m$^3$/s (50 MGD)
Figure 6.14: Shear Velocities and Consequent Resuspension Phases for Q=12 m³/s (274 MGD)
Figure 6.15: Shear Velocities and Consequent Resuspension Phases for $Q=24\ m^3/s$ (548 MGD)
Table 6.1. Sensitivity Analysis to the parameters $K_{D,TSS}$ and $K_{BOD,TSS}$

<table>
<thead>
<tr>
<th>Parameter varied</th>
<th>Reference value multiplied by $\hat{\epsilon}$</th>
<th>RMSD (mg/L)</th>
<th>Maximum Deviation (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{D,TSS}$</td>
<td>0.667</td>
<td>1.50</td>
<td>1.38</td>
</tr>
<tr>
<td>$K_{D,TSS}$</td>
<td>1.333</td>
<td>0.75</td>
<td>1.01</td>
</tr>
<tr>
<td>$K_{BOD,TSS}$</td>
<td>0.667</td>
<td>1.04</td>
<td>0.34</td>
</tr>
<tr>
<td>$K_{BOD,TSS}$</td>
<td>1.333</td>
<td>0.97</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Chapter 7. Discussion

Previous analyses of $SOD_{NR}$ studies (e.g. Cerco et al. 1992) have noted the importance of reporting the hydrodynamic parameters under which $SOD_{NR}$ is measured and the general deficiency of many past studies in doing so. In this study, hydrodynamics was analyzed using CFD, which has previously proven to be suitable for use in SOD chambers (Arega and Lee, 2005). The shear velocity $u^*$ is a key parameter, as it controls the value of the mass transfer coefficient and the frequency of near-wall turbulent fluctuations (O’Connor and Hondzo, 2008; O’Connor et al., 2009). $u^*$ values are therefore reported with the $SOD_{NR}$ measurements in Table 5.5. These values are based on CFD simulations where roughness was estimated from sediment sample analysis, which does not account for any potential bedforms or roughness associated with the organic mat at the surface. This may potentially affect the $u^*$ values. The low ambient DO conditions and the low flow velocity threshold for sediment resuspension allowed only a limited number of field trials at each sample station. Therefore a site-specific relationship between $u^*$ and $SOD_{NR}$ prior to the point of resuspension, which would have elucidated the relative effects of water-side and sediment-side controls, could not be formulated. However, measured $SOD_{NR}$ values were sensibly higher than previous measurements in Bubbly Creek in 2006 using a similar chamber system with no flow circulation, where $SOD_{NR20}$ values varied between 1.38 and 3.48 g/m$^2$/day (MWRDGC, 2007). This suggests that the DO flux is controlled by water-side conditions, as a small increase in $u^*$ results in a substantial flux increase. Furthermore, it is likely that in the case of Bubbly Creek that sediment-side processes never become fully rate-limiting on DO flux in the mainly fine-grained sediments, because resuspension tends to occur before the hydraulic conditions are such that DO is delivered through the diffusive sublayer at a sufficient rate to exceed consumption rates in the highly organic, nutrient-rich sediment.

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1 Work presented herein is included in the publication Waterman et al. (In press), posted ahead of print with permission from ASCE. The author acknowledges the contributions of the coauthors of that publication: Andrew R. Waratuke, Davide Motta, Yovanni A. Cataño-Lopera, Heng Zhang, and Marcelo H. García.
Another important hydrodynamic characteristic in $SOD_{NR}$ measurements is turbulence in the chamber outer region, which is reflected in the calculated values of $u^\ast$. The spatial distribution of $u^\ast$ is illustrated in Figure 4.4; however, at a given point, the $u^\ast$ is effectively a temporal mean averaged over turbulent fluctuations. Sanford (1997) suggests that variance in $u^\ast$ is likely smaller in natural systems than in experimental enclosures and recommends reporting the variance of $u^\ast$ in addition to the mean in order to characterize important benthic processes. This is due to disproportionately high water column turbulence ($k$ or $\varepsilon$) relative to near-wall hydrodynamics ($u^\ast$) that is common in experimental enclosures when compared to a natural system (Sanford, 1997; Crawford and Sanford, 2001). Direct measurements of temporal variability in the hydrodynamics of the sampler or Bubbly Creek were not performed; however, some inferences regarding variability can be made by comparing mean $\varepsilon$ and $u^\ast$ values between the chamber 3D model and a Bubbly Creek two-dimensional (2D) depth-averaged model (Motta, 2008). For a flow rate of 35 m$^3$/sec (just under the mean Bubbly Creek CSO discharge of 37.8 m$^3$/sec), the average shear velocity ($u^\ast_{ave}$) and the 5$^{th}$ and 95$^{th}$ percentiles of the spatial distribution ($u^\ast_{5\%}$ and $u^\ast_{95\%}$) computed by the 2D model are 2.4 cm/sec, 0.63 cm/sec, and 4.5 cm/sec, respectively. The associated values of $\varepsilon_{ave}$, $\varepsilon_{5\%}$, and $\varepsilon_{95\%}$ are 0.22 cm$^2$/s$^3$, 0.016 cm$^2$/s$^3$ and 0.80 cm$^2$/s$^3$. In comparison with Tables 4.1 and 4.2, showing values calculated within the chamber portion of the sampler, it is evident that while the sampler does achieve $u^\ast$ values similar to Bubbly Creek, the $\varepsilon$ values within the chamber are considerably higher. Assuming that temporal variance in $u^\ast$ is consequently larger in the sampler per Sanford (1997), the effect on the oxygen uptake rates could be significant under certain conditions. Characterizing the temporal variability of the hydrodynamic parameters and the consequent impact on $SOD_{NR}$ would be a worthwhile future effort.

Hydrodynamics within the sampler also exerts a significant influence on $SOD_r$. Turbulence parameters from CFD simulations are reported for the sampling system as a whole in Table 4.3, because oxygen consumption processes occur throughout the whole system when sediment is resuspended. The level of turbulence controls mixing, which is important to chemical reactions, along with bacterial physiology and oxygen uptake (e.g. Bergstedt et al., 2004; Al-Hamoud et al., 2007). The hydraulic effect on microbial oxygen uptake is commonly quantified using the
Sherwood number (Sh), which is defined as the ratio between the uptake rates by a microbial cell in a flow and in a stagnant fluid; and Sh is usually expressed as a function of the Peclet number (Pe), which is the ratio of advective to diffusive transport (Logan and Dettmer, 1990). Either the mean velocity or the turbulent fluctuations have been used as the representative velocity scale in the Pe calculation. Investigating Sh correlations is beyond the scope of the current study, however it is important to note that SODR certainly has some dependence on turbulence that is not expressed in Eq. (23). This suggests that additional work on the relationship between turbulence and oxygen uptake rate would be appropriate so that the results obtained within the sampler can be properly scaled to turbulence conditions characteristic of natural waterways.

Applying Eq. (23) to Bubbly Creek or other sites also requires additional consideration of the potential effect of scaling from the small spatial and temporal scales of the sampler measurements to the larger spatial scale of the actual waterway over the entire duration of a CSO event and subsequent period of sediment deposition. Knowledge of the processes of production, consumption, and mass transport in the water column of either DO or reduced chemical constituents that can be oxidized by DO would assist in this regard. Because the present study represents a largely unexplored field of inquiry, the exact nature of these processes when associated with resuspended sediment is not well understood and their characterization is beyond the scope of the investigation. At this point we can speculate on the issues that should be addressed in order to quantify those processes and lead to a more accurate implementation of the findings into a numerical model. In the water column, the sources of dissolved oxidizable compounds available for consumption through chemical oxidation and biological respiration are the fluxes of these compounds from sediment pore water entrained during sediment resuspension and the mineralization of the entrained particulate organic matter (POM). The fast kinetics of consumption of dissolved pore water compounds from the slower kinetics of POM mineralization have not been separated. The fast reaction would presumably have a substantial influence on the short field tests (typically ~20 minutes), but may not impact the longer-term DO expenditure at the prototype scale. With this in mind, it is noted that on Figure 6.2, the points at high DO concentration diverged significantly
from the fitted curves, having a very high oxygen uptake rate. Also, during the laboratory experiments a period of very rapid oxidation upon mixing sediment into solution was observed, indicated by a short very steep portion of the oxygen drawdown curve, followed by a more gradual typical-shaped nonlinear decline; see Appendix C. Fast consumption kinetics may be the cause. It is possible that when sediment is first put into suspension, a release of dissolved chemical constituents from the pore space of the sediment into the oxygen-rich water is accompanied by rapid chemical oxidation. Once this initial burst of oxidation expends the dissolved constituents, the slower mineralization of organic material bound onto the sediment particles may proceed in a more gradual manner; the different mechanisms of oxidation may explain why the oxygen uptake rates for the high values do not match well with the remainder of the curve. Regarding the slower kinetics of bacterial-mediated mineralization, longer time scales would likely be accompanied by an increase of the bacterial population, suddenly supplied with a favorable environment of organics, nutrients, and turbulent mixing (Wainwright, 1987; Bergstedt et al., 2004). The consequent increase of oxygen consumption would be at least partially counteracted by a non-negligible decrease of the sediment-derived BOD, as commonly expressed in coupled BOD-DO differential equations (e.g. Ambrose et al., 1988). It is also noted that entrained pore water contains low DO concentrations. The effect of low DO pore water diluting the DO concentration of a deep well-mixed body of water is certainly minor; however, its effect in the smaller control volume of the sampling system may be more substantial. Quantifying the relative effects of these various factors would help in applying the findings to larger spatial and temporal scales.

Even though explicit quantification of all mentioned processes is not provided in the present study, the structure of Eq. (23) with its four components should prove to be generally applicable to other sites; however some caution should be used in its application. $C_{TSS}$ has been used as a surrogate for $C_{BOD}$, and not all sediments will have the same percentage of oxidizable material. In its present form, the empirically determined value of $K_{O,TSS}$ captures all the variability in sediment conditions. The significant variation in $K_{O,TSS}$ values in the simulations of the sink term is most likely due to variations in the BOD associated with the sediment in different locations. However if $C_{BOD}$ was explicitly characterized as a function of $C_{TSS}$ and
incorporated into the model, a non-varying $K_{D,TSS2}$ would likely result. It would also allow expenditure of BOD over longer time scales using coupled BOD-DO equations, which would be a significant improvement to the formulation. In its current form, caution should be used regarding the values for the coefficients $A_2$, $K_{BOD,TSS}$, and especially the rate coefficient $K_{D,TSS2}$, as the sensitivity analysis has highlighted. As indicated, $K_{D,TSS2}$ is certainly highly dependent on the sediment type. Equation (23) also involves an inherent connection between the coefficients $K_{D,TSS2}$ and $A_2$, due to the need, imposed by the field conditions, of evaluating oxygen uptake rates relative to the rate at low $C_{DO}$ (2.0 mg/L). If field conditions or modified experimental methods allow the evaluation of uptake rates relative to higher DO concentrations, then $K_{D,TSS2}$ and $A_2$ should be replaced with $K_{D,TSSx}$ and $A_x$, where $x$ represents the new standard $C_{DO}$ value. However, it should be noted that the multiplication of $K_{D,TSSx}$ and $A_x$ is theoretically constant regardless of the $C_{DO}$ standard used in their evaluation. For application of the sink term to other sites, it is recommended that site-specific studies of $K_{D,TSS2}$, $A_2$ and $K_{BOD,TSS}$ be performed until sufficient data has been collected across many sites to determine general values of these coefficients.

As regards sediment erosion, future extension of the correlation between $u^*$ and $C_{TSS}$ will allow derivation of a spatially variable formulation for sediment entrainment rate to be implemented into a numerical model (e.g. García and Parker, 1991). The value of $u^*$ adopted in this analysis is the average value over the exposed sediment area; however, as shown in Figure 4.4, small regions of exposed sediment experience $u^*$ values 3 times in excess of the average value, which indicates that resuspension could be concentrated in the regions characterized by high $u^*$. Modifications to chamber geometry could potentially make the $u^*$ distribution more spatially uniform. At this point it is unknown if sediment entrainment reaches a dynamic equilibrium where near-bed concentrations result from a balance between entrainment and deposition rates (García, 2008); or, alternately, if scour simply continues until entrainment reduces to zero due to increased resistance to scour with depth. This aspect is very important since it influences the distribution of suspended sediment in the water column at the prototype scale, and therefore will require additional analysis.
The U of I Hydrodynamic SOD Sampler is an initial effort to quantify in situ bed shear stress and sediment erosion generated by bed-parallel flow in conjunction with oxygen uptake rates. Field sampling and subsequent analysis revealed several potential modifications that could improve the overall system functionality: modifying the chamber geometry to create a more uniform distribution of shear velocity and a more longitudinally uniform diffusive boundary layer; implementing an optical DO probe and a turbidity sensor; developing a more sophisticated means of drawing water samples to analyze suspended sediment and separate the effects of chemical and biological kinetics; and developing a system to supply the sampler with oxygenated water at the start of each test so that DO will not be fully expended after a limited amount of trials. A more accurate method of measuring the oxygen uptake in the ambient water for use in Eq. (4), such as deploying a blank sampler with closed bottom (Murphy and Hicks, 1986), would be appropriate for studies focused on $SOD_{NR}$; on the other hand, accurately characterizing that value is less important when focusing on $SOD_{R}$. 
Chapter 8. Summary and Conclusions

Bubbly Creek in Chicago, Illinois, contains a deep bed of highly organic, nutrient-rich sediments. Additional characterization of the sediment composition was performed, confirming previous studies that found the sediment transitioned from coarse material (sand) with relatively low organic content at the upper end to fine-grained material (silt/clay) with high organic content at the lower end. Sediment oxygen demand was split into two separate components, relative to conditions without \( SOD_{NR} \) and with \( SOD_R \) sediment resuspension from the bottom. \( SOD_{NR} \) represents a surface oxygen sink (typical units are g/m\(^2\)/day), while \( SOD_R \) is a volume sink (units are mg/L/day in this study). A new in situ experimental apparatus, named U of I Hydrodynamic SOD Sampler, was designed and implemented to achieve high flow velocities and quantify both \( SOD_{NR} \) and \( SOD_R \). The U of I Hydrodynamic SOD Sampler was able to achieve shear velocities \( (u^*) \) in the range of 0.13 to 0.93 cm/sec, as determined through CFD (computational fluid dynamics) modeling of the system.

In absence of sediment resuspension, \( SOD_{NR} \) at 20°C varied between 6.7 g/m\(^2\)/day and 12.1 g/m\(^2\)/day when measured with shear velocity \( u^* \) in the range of 0.128 to 0.255 cm/s. These \( SOD_{NR} \) values are sensibly higher than those previously reported for conditions of quiescent water, which suggests that the effect of flow velocity in increasing the bottom SOD was verified in the field. However, it was not possible to establish a velocity-dependent formulation for \( SOD_{NR} \), due to the constraints imposed by the field conditions and the sampler itself, in particular because of the low velocity threshold for sediment resuspension. A theoretical analysis was provided in Section 6.1.2 that quantifies how \( SOD_{NR} \) may be reduced below the field-measured values when velocity is low.

With respect to sediment resuspension, the objectives of the study were to characterize the bed shear stress threshold at which sediment resuspension is initiated; to characterize the magnitude of resuspension as bed shear stress increases; and to characterize \( SOD_R \) as a

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1 Work presented herein is included in the publication Waterman et al. (In press), posted ahead of print with permission from ASCE. The author acknowledges the contributions of the coauthors of that publication: Andrew R. Waratuke, Davide Motta, Yovanni A. Cataño-Lopera, Heng Zhang, and Marcelo H. García.
function of the concentration of sediment in suspension. A number of significant findings were made in the process of meeting these objectives. Field experiments identified several phases of resuspension, and critical shear velocities were established for each:

(1) The Flaking Phase was characterized by a film of organic debris being scoured from the sediment surface at a relatively low shear velocity. The critical shear velocity to initiate flaking was found to be 0.17 cm/sec and did not appear to be dependent on the underlying sediment type.

(2) The Full Resuspension Phase involved the main sediment (under the film of organic debris) entering suspension, which caused a drastic increase in the oxygen drawdown. The critical shear velocity to cause predominantly fine-grained material to enter full resuspension varied between 0.37 and 0.76 cm/sec, depending on the sediment texture and the overlying water depth. For the sediments composed primarily of sand, the maximum shear velocity achieved with the sampler was not sufficient to cause full resuspension; however, critical shear velocities were calculated using standard sediment transport theory available for non-cohesive soils. The critical shear velocity for sandy sediment with $D_{50}$ equal to 0.25 mm was found to be 0.91 cm/sec to initiate sediment mobilization as bedload; and 2.54 cm/sec to initiate sediment entrainment into full suspension.

(3) A Bedload Partitioning Phase was speculated to have occurred in those soils with mixed fine- and coarse-grained components, where the bed material was mobilized, but with only the fine-grained and organic fraction entering suspension into the water column. Because transitioning between Flaking and Bedload Partitioning phases was indistinct, no attempt was made to quantify critical shear velocities associated with this intermediate phase.

The suspended sediment concentration $C_{TSS}$ was analyzed as a function of $u^*$ using graphical relations at each sample station separately. These findings can ultimately be used to establish a sediment entrainment rate. In conjunction with sediment transport modeling, the entrainment rate can be used to model $C_{TSS}$ achieved throughout the water column during an actual flow event. Hydrodynamic simulations of various flow rates utilizing the 2-D modeling of Motta (2008) allowed comparison of prototype flows with the experimental results. This modeling
yielded spatial variations of shear velocities at the prototype scale, which were evaluated in the context of the critical shear velocities identified during the field experiments. The simulations revealed that a 2.19 m$^3$/sec (50.0 MGD) low flow rate would be sufficient to induce flaking of organic debris in upper Bubbly Creek. A 12 m$^3$/sec (274.0 MGD) flow rate would result in the sandy streambed of upper Bubbly Creek being mobilized as bedload; with the remainder of the stream undergoing a mixture of flaking or full resuspension. A 24 m$^3$/sec (547.9 MGD) flow rate would result in portions of the sandy upper reach transitioning from bedload to full resuspension; and the entire lower portion of Bubbly Creek undergoing full resuspension.

The final objective was to characterize oxygen demand exerted under sediment resuspension conditions, $SOD_R$. The oxygen uptake rate associated with early Flaking Phase resuspension was found to be typically 2 times higher than the background $SOD_{NR}$. For the Full Resuspension Phase, it was typically an order of magnitude higher than $SOD_{NR}$, and laboratory data indicated it could reach several orders of magnitude higher for a high-concentration slurry. A relation characterizing $SOD_R$ as a function of $C_{TSS}$, dissolved oxygen concentration $C_{DO}$ and temperature was developed in Eq. (23), in a form parallel to first-order BOD consumption kinetics with Monod DO term. The analysis suggests that highly organic resuspended sediment can be considered a direct source of BOD as modeled by Motta et al. (2010). With additional data to develop sediment entrainment functions, it appears feasible to implement Eq. (23) into a hydrodynamic, sediment transport, and water quality model to evaluate DO concentrations during and following CSO events in Bubbly Creek; and to evaluate management strategies involving flow augmentation. With additional work to properly quantify the constants, it may also be feasible to use the general form of Eq. (23) in other portions of the Chicago area waterways (Polls and Spielman 1977). Future work to improve the sampler, to make the findings more broadly applicable, and to improve the general understanding of processes associated with resuspended sediment are outlined in the Discussion.
NOTATION

The following symbols are used in the paper:

\( A \) = surface area of exposed sediment in sampling chamber (L^2);
\( C_{BOD} \) = concentration of biochemical oxygen demand in oxygen equivalents (M/L^3);
\( C_{DO} \) = concentration of dissolved oxygen (M/L^3);
\( C_f \) = bed friction coefficient;
\( C_{TSS} \) = concentration of total suspended solids (M/L^3);
\( D \) = molecular diffusivity of dissolved oxygen in water (L^2/T);
\( D_{50} \) = median sediment diameter (L);
\( g \) = gravitational acceleration constant (L/T^2);
\( H \) = mean flow depth (L);
\( k \) = turbulent kinetic energy (L^2/T^2);
\( k_{ave} \) = turbulent kinetic energy; average of spatial distribution (L^2/T^2);
\( k_5 \) = turbulent kinetic energy; 5th percentile of spatial distribution (L^2/T^2);
\( k_{95} \) = turbulent kinetic energy; 95th percentile of spatial distribution (L^2/T^2);
\( k_S \) = roughness height (L);
\( K_1 \) = dimensionless constant of proportionality used in analysis of mass transfer coefficient;
\( K_A \) = reaeration rate coefficient (T\(^{-1}\));
\( K_{BOD} \) = half-saturation constant in Monod term for standard BOD (M/L^3);
\( K_{BOD,TSS} \) = half-saturation constant in Monod term specific to resuspended sediment (M/L^3);
\( K_D \) = deoxygenation rate coefficient at 20°C for standard BOD (T\(^{-1}\));
\( K_{D,TSS2} \) = deoxygenation rate coefficient specific to resuspended sediment at 20°C and \( C_{DO} \) at 2 mg/L (T\(^{-1}\));
\( Pe \) = Peclet number;
\( Q \) = flow discharge rate (L^3/T);
\( R \) = submerged specific gravity of sediment;
\( Re \) = Reynolds number;
\( Re^* \) = roughness Reynolds number;
\( Re_p \) = particle Reynolds number;
$R_h =$ hydraulic radius (L);

$\textbf{Sc} = \nu / D =$ Schmidt number;

$\textbf{Sh} =$ Sherwood number;

$S_i =$ individual DO source and sink terms (M/L³/T);

$SOD_{NR} =$ sediment oxygen demand with no resuspension; oxygen uptake rate as a surface sink (M/L²/T);

$SOD_{NR20} =$ $SOD_{NR}$ temperature-normalized to 20°C (M/L²/T);

$SOD_R =$ sediment oxygen demand with resuspension; oxygen uptake rate as a volumetric sink (M/L³/T);

$t =$ time (T);

$\hat{t} =$ dimensionless time used in sensitivity analysis;

$T =$ water temperature (°);

$u_* = (\tau_b / \rho)^{0.5} =$ shear velocity (L/T);

$u_{crit} =$ critical shear velocity to initiate Flaking Phase resuspension (L/T);

$U =$ mean longitudinal velocity (L/T);

$V =$ total volume of water enclosed in sampling system (L³);

$\nabla \cdot F_{C,D} =$ net convective and diffusive flux (M/L²/T);

$\Delta C =$ concentration difference across the diffusive sublayer (M/L³);

$\beta =$ mass transfer coefficient (L/T);

$\varepsilon =$ turbulent kinetic energy dissipation rate (L²/T³);

$\varepsilon_{ave} =$ turbulent kinetic energy dissipation rate; average of spatial distribution (L²/T³);

$\varepsilon_5 =$ turbulent kinetic energy dissipation rate; 5th percentile of spatial distribution (L²/T³);

$\varepsilon_{95} =$ turbulent kinetic energy dissipation rate; 95th percentile of spatial distribution (L²/T³);

$\Lambda_2 =$ coefficient required in Monod term incorporated in Eq. (23) = $1 / (C_{DO} / (C_{DO} + K_{BOD,TSS}))$

with $C_{DO} =$ 2.0 mg/L;

$\rho_s =$ sediment density (M/L³);

$\rho_w =$ water density (M/L³);

$\tau_b =$ bed shear stress (M/L/T²);

$\tau_* =$ dimensionless Shields’ stress;
\( \Theta_D \) = temperature correction coefficient associated with BOD in water column;

\( \Theta_S \) = temperature correction coefficient associated with \( SOD_{NR} \);

\( \nu \) = kinematic viscosity (\( L^2/T \));

\( \chi \) = coefficient to adjust lab-measured ambient water oxygen uptake rate to field conditions.
REFERENCES


Appendix A: MISCELLANEOUS MAPS AND FIGURES
Figure A.1: Chicago Area Waterways in vicinity of Bubbly Creek
Figure A.2: USACE 2005 Sampling Locations
Figure A.2 (cont.)
Figure A.3: Bathymetry Overview, 2006
Figure A.5: Bathymetry Detail, STA 1+00 to 4+00
Figure A.6: Bathymetry Detail, STA 4+00 to 7+00

2006 BATHYMETRY BY USGS
Figure A.7: Bathymetry Detail, STA 7+00 to 11+00
Figure A.9: Bathymetry Detail, STA 14+00 to 17+00
Figure A.10: Bathymetry Detail, STA 17+00 to 20+00
Figure A.11: Bathymetry Detail, STA 20+00 to 23+00
Figure A.12: Bubbly Creek Sludge Depth Profile.
Figure A.12 (cont.)
Appendix B: DO DRAWDOWN CURVES FROM FIELD EXPERIMENTS

Figure B.1: Trial 1A

Figure B.2: Trial 1B
Field Data
Linear Regression

Figure B.3: Trial 1C

Figure B.4: Trial 2A
Figure B.5: Trial 2F

Figure B.6: Trial 3A
Figure B.11: Trial 5A

Figure B.12: Trial 5B
Figure B.13: Trial 5C

Figure B.14: Trial 5D
Figure B.15: Trial 5E

Figure B.16: Trial 6A
Figure B.19: Trial 7B
Appendix C: DO DRAWDOWN CURVES FROM LABORATORY EXPERIMENTS

Table C.1: Laboratory Analysis of Solutions tested in Lab for DO Uptake

<table>
<thead>
<tr>
<th>ID</th>
<th>Sediment</th>
<th>T°(°C)</th>
<th>TSS (mg/L)</th>
<th>VSS (mg/L)</th>
<th>% Organic</th>
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<tr>
<td>Test #2B</td>
<td>M</td>
<td>21.8</td>
<td>60260</td>
<td>12790</td>
<td>21.2</td>
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<td>15350</td>
<td>3460</td>
<td>22.5</td>
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<td>Test #4</td>
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<td>7470</td>
<td>1700</td>
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<td>M</td>
<td>22.5</td>
<td>3630</td>
<td>900</td>
<td>24.8</td>
</tr>
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<td>Test #5B</td>
<td>C</td>
<td>24.0</td>
<td>3910</td>
<td>1160</td>
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<td>1560</td>
<td>440</td>
<td>28.2</td>
</tr>
<tr>
<td>Test #7</td>
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<td>992</td>
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<td>136</td>
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<td>81536</td>
<td>1012</td>
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<td>3097</td>
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<td>22.5</td>
<td>13180</td>
<td>2860</td>
<td>21.7</td>
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</table>

The orange-shaded cells yielded results that did not correspond with the lab notes regarding the amount of sediment added to solution relative to the other samples using the same sediment. Dr. Heng Zhang indicated that difficulty getting good results with Sediment D was probably due to the high percentage of heavy solids which causes interference in the test results.
Figure C.1: Lab Test #1, Ambient Water

Temp = 19.96°C

Ambient Water test (see Test #10 for a longer test on ambient water)

Figure C.2: Lab Test #2

Temp = 20.75°C
Figure C.3: Lab Test #3

Figure C.4: Lab Test #4
Figure C.5: Lab Test #5

Figure C.6: Lab Test #5B
Figure C.7: Lab Test #6

Figure C.8: Lab Test #7
Figure C.9: Lab Test #8

Figure C.10: Lab Test #9
Figure C.11: Lab Test #10, Ambient Water

Figure C.12: Lab Test #11
Figure C.13: Lab Test #12

Figure C.14: Lab Test #13
Figure C.15: Lab Test #14

Figure C.16: Lab Test #15

141
Figure C.19: Lab Test #18

Figure C.20: Lab Test #20
Figure C.21: Lab Test #21

Figure C.22: Lab Test #22
Figure C.23: Lab Test #23

Figure C.24: Lab Test #24
Figure C.27: Lab Test #27

Figure C.28: Lab Test #28
Figure C.29: Lab Test #29

Figure C.30: Lab Test #30
Appendix D: SETTLING VELOCITY AND PARTICLE SIZE DATA FROM LISST-ST

Figure D.1: Settling Velocities, Sediment L

Figure D.2: Particle Size Distribution, Sediment L
Figure D.3: Settling Velocities, Sediment K

Figure D.4: Particle Size Distribution, Sediment K
Figure D.5: Particle Size Distribution, Sediment I

Figure D.6: Particle Size Distribution, Sediment I
Figure D.7: Particle Size Distribution, Sediment G

Figure D.8: Particle Size Distribution, Sediment G