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Resuspension of E. coli Under Controlled Flows and Stream Bottom Sediments

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Resuspension of *E. coli* under controlled flows and stream bottom sediments

by

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Nomenclature

List of Abbreviations

Abbreviation	Full Name
cfu	Colony Forming Units
CSO	Combined Sewer Overflow
CWA	Clean Water Act
EPA	Environmental Protection Agency
EPS	Extra Polymeric Substance
FC	Fecal Coliforms
GI	Gastrointestinal Illness
LISST	Laser In-Situ Scattering Transmissometer
MPN	Most Probable Number
NAR	Nalidixic Acid Resistant
NPDES	National Pollutant Discharge Elimination System
NTU	Nephelometric Turbidity Units
qPCR	Quantitative Real Time Polymerase Chain Reaction
SWAT	Soil and Water Assessment Tool
TMDL	Total Maximum Daily Load

Variables

a coefficient for the effects of particle packing on the critical shear stress attached τ_c [L^2]

a_u coefficient for the effects of particle packing on the critical shear stress unattached τ_c [L^2]

b coefficient for the effects of particle packing on the critical shear stress attached τ_c [$L^3 M^{-1}$]

bu coefficient for the effects of particle packing on the critical shear stress unattached τ_c [-]

c_3 $\pi\rho g(s\text{-}1)/6$, coefficient for the effect of clay on the critical stress τ_c [$M L^{-2} T^{-2}$]

c_5 coefficient for the effect of clay on the critical stress τ_c [$M L^{-1} T^{-2}$]

C_a concentration of *E. coli* attached to sediment in the water column [$\# L^{-3}$]

C_{ab} concentration of *E. coli* attached to sediment in the bed [$\# L^{-3}$]

Cu concentration of *E. coli* attached to sediment in the water column [$\# L^{-3}$]

Cu_b concentration of *E. coli* unattached to sediment in the bed [$\# L^{-3}$]

d diameter of sediment particles to which *E. coli* attach [L]

E_{ao}	coefficient in the predicted resuspension rate of attached particles [L T^{-1}]
E_{uo}	erosion rate at the threshold of erosion of unattached particle [L T^{-1}]
Fb	binding force as a function of the particle diameter and specific gravity [-]
g	acceleration of gravity [L T^{-2}]
n_a	exponent in the predicted resuspension rate attached [-]
n_u	exponent in the predicted resuspension rate unattached [-]
Q	discharge [L^3 T^{-1}]
R	hydraulic radius [L]
R_a	predicted attached resuspension rate [# L^{-2} T^{-1}]
R_{ac}	calculated attached resuspension rate [# L^{-2} T^{-1}]
R_u	predicted unattached resuspension rat [# L^{-2} T^{-1}]
R_{uc}	calculated unattached resuspension rate [# L^{-2} T^{-1}]
S	slope [-]
SA	Surface Area [L^2]
S_{y_i}	relative sensitivity to y_i [-]
t	time [T]
y_i	uncertainty in S_{yi}
ρ	water density [M L^{-3}]
ρ_b	bulk density of the sediment [M L^{-3}]
τ_b	bottom shear stress [M L^{-1} T^{-2}]
τ_c	critical shear stress for cohesive sediment [M L^{-1} T^{-2}]
τ_{cn}	critical shear stress for non-cohesive sediment [M L^{-1} T^{-2}]
δ	Standard deviation
[-]	unit less parameters
#	colony forming units

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Abstract

Elevated pathogen levels are the leading cause of water quality impairments in the waterways of the United States. Pathogens can enter waterways through combined sewage overflow, agricultural practices or wildlife. These pathogens survive in various phases but once attached to particles they can become persist in the sediment bed. Pathogens in the sediment bed can resuspended during high flows and when ingested cause gastroenteritis among children and immune compromised individuals. This research promotes the development of better methods to model bacterial pathways in the environment. The first goal of the study was to measure *E. coli* resuspension from various sediments over a range of flow rates. The second goal of the study was to calculate unattached and attached *E. coli* resuspension and compare calculated values to predicted resuspension rates.

The experiments were conducted in a recirculating plexiglas flume 9.1 m in length. Three different bottom sediments were evaluated: sand, sand-silt, and sand-silt overlain with biofilm. The water samples were collected at two locations downstream from the initial flume inlet. At each location, nine samples were collected in a grid pattern. For each bottom sediments there were multiple experiments at flows set by the critical shear stress. Two runs were selected below critical shear stress and one run above critical shear stress for each bottom sediments. A duplicate run under critical shear stress was completed for all three of the bottom sediments at a higher water depth. Various background and sediment samples were also collected to characterize the experiments and complete a mass balance on the *E. coli* concentrations. Once samples were taken at the flume, they were enumerated using standard membrane filtration techniques at the water quality research laboratory at Iowa State University. Composites of the nine points were compiled based on velocity analysis, and tested for total and unattached concentrations of *E. coli*, in order to obtain attached *E. coli* values. Using the two sample locations, resuspension was calculated for the attached and unattached fractions. Using a SAS statistical package, correlations and comparisons were completed on the collected data. Predicted values obtained using a sediment resuspension model (Lick 2009; Pandey et al. 2012) were compared to values calculated from the experimental data. The model equations were then calibrated by using the calculated data.

Attachment ratios were assessed using filtration techniques by applying different pore size filters. During the experiments the attachment ratios increased as particle sizes in the bottom sediments size decreased. The percent of attached *E. coli* decreased after the critical shear stress was surpassed. The percent of attached *E. coli* was also impacted by depth of the water. Between the 15 cm and 23 cm depth the sand attachment decreased by 66%, sand-silt increased by 34%, and biofilm decreased by 69% over the two sample collection locations. There was a statistical difference between the sediment type and flow rate compared to the attachment found in the flume. The calculated unattached *E. coli* resuspension rate was 1.32E-6 cfu/m^2/s for sand, 1.03E-6 cfu/m^2/s for sand-silt, and 1.78E-6 cfu/m^2/s for biofilm. The calculated attached *E. coli* resuspension rates were 3.84E-6 cfu/m^2/s for sand, -2.84E-6 cfu/m^2/s for sand-silt, and -8.06E-6 cfu/m^2/s for biofilm, where the negative values indicate deposition. Using the measured values and calculated values, the various parameters were input in the model. The statistical analysis of the regression found an r^2 value of 0.85 for the unattached *E. coli* resuspension model in comparison to the calculated *E. coli* resuspension values. The statistical analysis of the regression found an r^2 value of 0.91 for the unattached *E. coli* resuspension model in comparison to the calculated *E. coli* resuspension values. The negative resuspension values indicate deposition and were not used to predict resuspension in the model. The resuspension was found to be low in comparison similar field studies by Pandey and Jamieson. The differences of the flume conditions and lower flow rates than in other resuspension studies could have caused the differences in calculated resuspension.

There is a lack of knowledge and ability to track particles unattached pathogens in stream environments. It is possible to model attached *E. coli* resuspension with sediment equations based on the results of this study. The unattached fraction still needs further research to assess the risk of different resuspension parameters. The flume could be used to study further sediments and higher flow rates to examine effects on resuspension. The equations developed should be tested in field experiments, to confer and further calibrate the model. Calibrated equations need to be tested in field environments to explore how turbulent flow may affect the resuspension of various bottom sediments.

Chapter 1 Introduction

Water quality has become a global issue due to scarcity and increasing change in global weather patterns. Freshwater has especially been protected in the United States under the Clean Water Act (CWA), which is intended to maintain the integrity of the nation's waters. The CWA requires a list to be made of the waters not meeting the specified limits on pollutants. Programs are developed to monitor and help reach concentration goals in order for waters to then be removed from the impaired wasters list (USEPA 2009). Pathogens are the leading violation of water quality standards (USEPA 2002) and can be particularly harmful to human health. Ingestion of these pathogens, through recreational contact, can cause gastroenteritis. Pathogen detection often indicates a compromised waterbody by fecal matter, as pathogens are found in the lower intestines of warm blooded animals.

After the pathogens are released into the environment, there is a large amount of uncertainty of the microbial transport pathways. If pathogens reach a waterbody, there are various outcomes which can occur including deactivation, attachment and deposition. Once pathogens reach the sediment bottom, chances of survival increase as they are protected from predators and higher amounts of nutrients are available. These pathogens in sediments have been found to have higher deactivation times then pathogens in the water column which are freely suspended. Once the pathogens reach the sediment bed and survive, they can become a potential source of pathogens during high flow events. They can also be resuspended during any event which moves the sediment. Sediment disruptions include waves, and wind action as well as large weather patterns such as hurricanes (Fries et al. 2006; Fries et al. 2008; Ge et al. 2010). A study of the effects of bottom sediments types and different flow rates below and above critical shear stress would assist in modeling the resuspension of pathogens in stream sediments.

Models have a difficult time estimating bacteria resuspension due to the lack of research on the amount and properties which effect resuspension. Current models often ignore resuspension (Petersen et al. 2009) and can underestimate the amount of pathogens in the water columns. During drought periods, substantial deposition of particles, and therefore *E. coli*, can occur due to lower flow rates; however if the period of drought is followed by a

period of higher flow, pathogen and sediments loads in the stream can resuspend. Other models estimate resuspension linearly or based on partitioning coefficients (Russo et al. 2011). Attachment has been correlated to various factors; however resuspension has yet to be fully understood. Models of sediment resuspension have been established, yet no models of pathogens in attached and unattached phases have been modeled in a flume using sediment resuspension equations. Using previous sediment resuspension equations the attached and unattached movement was investigated.

Goals & Objectives

The main goal of this study was to improve understanding of how different bottom sediments and flows impact in-stream bacterial attachment fractions and resuspension by:

- Measuring the attachment ratio over three different bottom sediments (sand, sand-silt, and sand-silt overlain with biofilm), three flows, and two water depths
- Calculating the attached and unattached resuspension

The second goal of this study was calibrate a sediment model using the calculated unattached and attached resuspension measured in the flume by:

- Modifying sediment resuspension equations to model the bacteria resuspension process
- Calibrating the model using the calculated resuspension and compare to model

Hypothesis

During the preparation for this study various hypotheses for expected outcomes were identified.

- The increased shear stress will increase bacterial attachment
- The sediment types will significantly affect the resuspension and attachment of the particles
- Attachment will be higher among biofilm bottom sediments
- The resuspension rate of attached *E. coli* will be proportional to the resuspension rate of sediment

- The two depth comparisons will result in lower resuspension for the higher depth and different attachment ratios
- There will also be higher resuspension with higher flow rates
- Resuspension of unattached *E. coli* will occur at lower shear stresses than for attached *E. coli*

Thesis Organization

The goal of this study was to measure resuspension of *E. coli* in various flows and bottom sediments. Chapter 2 consists of a literature review research concerned with movement of microbes and current models of resuspension. Chapter 3 is a paper to be submitted to a peer reviewed journal. Chapter 3 presents a detailed looked at the measured resuspension achieved in the flume and comparison of resuspension values. Chapter 4 is a conclusion chapter including implications and future work which could extend the knowledge in further research.

Chapter 2 Literature Review

Water Quality-Pathogen Impairments

Access to clean water is often listed as one of the essential human rights. The United Nations (UN) calls for decrease in population without sustainable access to safe drinking water (Scachs 2005) under the UN millennium goal number seven. Access to drinking water is being added as a constitutional right in certain countries, such as South Africa, Kenya, Sambia, Colombia, Uruguay, and India (Hildering 2004; Riedel 2006). The scarcity of fresh and clean water has become more prominent with the increase in population and changes in global weather patterns. This sacristy leads to more contaminated water due to improper management. An estimated 120 million cases of gastrointestinal illness (GI) are caused by bathing in coastal waters polluted with fecal matter (Shuval 2003). Various studies have proven that fecal contamination leads to illnesses among swimmers (Marion et al. 2010; Sinigalliano et al. 2010; Wade et al. 2010). The issue is not limited to bathing and swimming, recreation interactions also are an issue. Water ingestion has been shown to be 3.5-4 mL of water during limited recreation activities in comparison to 10 mL which are observed during swimming (Dorevitch et al. 2011). The fresh waters currently available are becoming scarcer and should be protected from fecal contamination. Fecal contamination causes a majority of the gastrointestinal illness in children, elderly and immunocompromised. Lack of access to clean drinking water is the number one cause of infant mortality throughout the world.

Waterborne pathogens are attributed to fecal deposition. Pathogens include total coliforms, fecal coliforms, *E. coli*, and enterococci. Pathogens, such as *E. coli*, are found in the intestines of warm blooded animals. Detection of pathogen indicates contact with fecal matter in the water source. The most studied pathogen, *E. coli*, has been best correlated with freshwater system health effects and Enteroccoccus has been correlated with marine system health effects (Halliday and Gast 2011). Due to concerns of water quality, detection of fecal contamination is important for both recreation and source water usage.

E. coli is used as a major indicator organism due to its high correlation with fecal matter and easily culturable (Dufour 1984). The negative side effect of using fecal coliform

(FC) membrane filtration is the incubation for 24 hours for full cultures to be produced. The cultures are measured by colony forming units (cfu) per one hundred milliliters of water. There are quicker methods of fecal detection such as real time Polymerase Chain Reaction (qPCR). These methods are more expensive and require highly trained staff; therefore they have not become as widespread as membrane filtration. Standard methods of detection have not changed to match the growing demand of real-time data.

The data collected on *E. coli* concentrations is often required by and reported to the U.S. Environmental Protection Agency (EPA). The EPA, through the Clean Water Act requires states to develop an impaired waters list based on various criteria. Fresh waters can become impaired through a number of ways including, salinity, pesticides, sedimentation, or xenobiotics released through human interaction. Impaired, according to the EPA, is any waterbody with a chronic or reoccurring violation of standard water quality criteria (USEPA 2011). The impaired waters list details the impaired waters of each state and identifies the impairments the waterway. After a waterbody is added to the list, the EPA sets goals through the Total Maximum Daily Load (TMDL) program (USEPA 2009). This requires states to test, record and report on water quality for each impaired water body. Pathogens impairments are the number one cause of impairment (USEPA 2010) for all United States waterways. It's estimated that 20,000 waterway are currently impaired due to pathogens and the cost of implementing the practice of TMDL program is 1 to 3.4 billion dollars annually (USEPA 2002).

The TMDL program assist in setting limits on the load of pollutants that can be added from various point and nonpoint sources into waterways. A point source is a load that is discharge from a specific location whereas non-point sources are released from multiple sources in a larger area (USEPA 2011). Many states classify waters as impaired due to pathogens and set TMDLs based on concentrations of the main fecal indicator, *E. coli* (USEPA 2000). Most of the bacterial load has been found to derive from nonpoint sources such as wildlife, agriculture, and leaky septic tanks (Ge et al. 2010). After bacteria enter the waterbody from various point and nonpoint sources, they may attach, settle, persist, grow, and resuspend in the sediments of waterways. It has been found that bacteria in sediments act as a source of bacteria during high flow events, where bacteria are resuspended from

bottom sediments into the water column. The resuspension will also depend on a number of factors including the type of bottom sediments in the waterways and flow rates. Currently the TMDL's do not include resuspension of sediments and attached microorganisms, which may cause a higher concentration of *E. coli* in the water column.

Microbial Sources

Pathogens are found in the intestines of warm blooded animals. The detection of pathogens leads to the conclusion that fecal matter has been in contact with a water source. Pathogens include total coliforms, fecal coliforms, *E. coli*, and enterococci. *E. coli* has historically been used as an indicator organism due to the ease of culturablity and low costs of processing.

Microbial pathogens in the water environment come from assorted sources. There are also various risks with each pathogenic source; humans are more susceptible to human pathogens. Soller (2010) investigated other sources of pathogens and found a risk associated with exposure by gull, chicken, or pigs are lower than human source risk. Sources of pathogens are a derived by a mixture of point and nonpoint sources. Examples of nonpoint sources include tile drainage, runoff from agricultural lands, runoff from confined feeding operations, infrastructure leaks, and wildlife contributions. Examples of point sources are categorized as runoff waste water treatment plant effluent and combined sewer overflow. Due to the nature of nonpoint source pathogenic releases are difficult to enumerate.

Cattle have been shown to be a source of nonpoint pathogens for streams. Sinclair (2009) was able to show that higher amounts of bacteria were found in rural basins with cattle than urban basins. Muirhead found that cow crossings were a statistically significant source of *E. coli* contamination (Muirhead et al. 2005) and the unattached cells can become highly mobile. The cells for the study were mixed including cowpats and cowpats mixed with soils. The concentrations of *E. coli* in the water due to runoff was 4-6 log/g of dry weight, whereas the concentration off of cowpats were 5-8 log/g of dry weight. Hotspots, cow crossings, can affect the concentrations downstream without much dispersion (Cho et al. 2010). With this type of nonpoint source, Collins was able to investigate the riparian buffer strips improvement of water quality near cattle crossings (Collins and Rutherford

2004). When looking at contaminates form a recreational standpoint the same risk is attributed to cattle feces than the human fecal coliforms (Soller et al. 2010). Cattle, however, are not the sole source of pathogenic concentrations in streams (Harmel et al. 2010). There have been other studies looking at the sources of fecal contamination, including wildlife as a major component (Kim et al. 2010). Deposition of wildlife fecal material has also been a major issue while modeling resuspension and loads (Kim et al. 2010).There have been measurable amounts of *E. coli* found in groundwater around sewage pipes due to leaks. Other studies are looking at various transport behaviors once pathogens infiltrated in the stream. Artificial floods caused by gate opening and of Nalidixic Acid Resistant (NAR) tracer bacteria, completed by Nagles, suggested removing livestock from stream channels to stop direct deposit (Nagels et al. 2002). Nagels showed the direct deposits were also responsible for the mobilization of fine grained sediment and bacteria which were well correlated. Sources in agricultural area fecal indicator bacteria and intestinal enterococci were measured and the values ranged between 1.4 $x10^3$ and 4.0 x 10^5 *E. coli*/100mL and sediment concentrations to range between 2.1 $x10^2$ and 3.3 x 10^5 *E. coli* /100mL. However, agriculture is no solely responsible for the numbers of pathogens found in streams, as point sources also contribute to concentrations.

Point source contributions come from industrial outfalls, wastewater treatment plants and combined sewage overflows. Wastewater treatment plants also provide a literal pipeline of microbial source. Outtara showed point sources are predominating in this stream system source of pathogens (Ouattara et al. 2011). Currently no regulations are placed on the effluent concentrations of pathogens at wastewater treatment plants. The EPA, however, is looking into programs which would limit the amount of pathogens released into the environment. Many cities, especially older cities, still have combined sewage overflow (CSO). Cities such as these release large amounts of untreated waste which cause large amounts of nutrients and pathogens to be released in a relatively short amount of time (Passerat et al. 2011). Passerat (2011) studied a case of CSO release in a outfall of Paris, France in the summer of 2008. This study measured the *E. coli* concentration to be $1.5x10^6$ *E. coli*/100 mL during the overflow. Releasing pathogens to the environment causes unnaturally high concentrations to be found in the areas around the outfalls.

Pathogens can move through various routes once in the environment. Microbes can remain attached to particles and runoff with rain events. Microbes can also be removed from source matter and travel unattached during runoff events. Rainfall events usually trigger the introduction of pathogens into streams, although direct deposit can also contribute to water quality degradation.

Microbial Transport in Surface Waters

Microbial transport has captured scientist's attention due to its increased importance in water quality. Government agencies and modelers have come to the realization that in order to understand environmental transport of pollutants, interdisciplinary knowledge is necessary including various disciplines such as fluids, chemistry and microbiology. Researchers must work to understand the movement and transportation of microbe environment by looking at attachment, settling, survival rates and resuspension.

The various point and non-point sources often lead to elevated levels of *E. coli* concentrations in sediment and water columns. There are many factors effecting microbial transport. Microbes can be found in three different states in waterways, 1) unattached microbe; 2) attached microbe; 3) resuspended microbes. The unattached microbes are osmotically similar to water and tend to flow in the same velocities without sedimenting. These microbes are freely-suspended and may create bonds with other particles due to electro potential attractions, decreasing their buoyancy and therefore settling faster. Planktons are mostly organic matter and contain many organisms. The attached microbes tend to be associated with an organic or inorganic conglomerate. The attached particles can be superficially attached or be completely sorbed into the particle. Sorbed particles are more difficult to remove from sediment and often require physical removal (Berry 1991). For this study sorbed and attached are similar and henceforth shall be referred to as attached.

The first state as an unattached microbe the likelihood for sedimentation or deposition is low and is considered negligible in most cases. The second state is an attached microbe on a particle, which will also have similar deposition rates as the attached sediment particle. Lastly, the microbe could be attached in the sediment bed and resuspend. In the third case during resuspension the microbe could become dislodged and become unattached

or the particle could remain attached and settle back into the sediment bed (Pachepsky and Shelton 2011). Many previous works on the topic of attachment and resuspension (Arnon et al. 2010; Fries et al. 2008; Jamieson et al. 2005; Pachepsky et al. 2006; Rehmann and Soupir 2009) call for further investigation into the attachment ratios of microbes to be completed. There is also on going work on pathogenic survival, and resuspension. The resuspension particularly is not understood in sediment bed.

Pathogenic Survival

Once a pathogen has moved into the environment there are a number of factors effecting the survival within the confines of the sediment and water column. Previous studies have determined that fecal bacterium persist as a source in stream beds (Droppo et al. 2009; Haller et al. 2009). Research is needed regarding long-term survival and deactivation. Deactivation occurs when a cell is no longer culturable, dying or lysis. *E. coli* concentration decreases by orders of magnitude within a matter of hours outside of an ideal host environment, in this case the environment of the lower intestine. However, if attachment occurs, deactivation can take much longer depending on environmental, water, and sediment conditions. Conditions influencing the deactivation time include organic matter, salinity, sediment fractionation, solar radiation, predation and sediment size (Burton et al. 1987; Garzio-Hadzick et al. 2010; Haller et al. 2009; Jamieson et al. 2005). These conditions cover the environmental, water column and sediment impacts.

Environmental impacts on survival rates such as temperature and solar radiation are very important once the microbe has reached the waterbody. The lower temperatures found outside of the human body limit pathogenic survival, due to optimum growing temperature for fecal bacteria being human body temperature of 25-35^{o}. However, pathogens have been found to survive at 4^{o}C, indicating the ability to survive winters in sediments (An et al. 2002). Solar radiation also causes a large amount of deactivation in streams; however sediments are shielded from sunlight in the stream beds. There is also a seasonal variation in the amounts of *E. coli* found in streams and studies have found *E. coli* concentrations are higher during the winter due to less predation by stream prokaryotes (Pachepsky and

Shelton 2011). This leads to a reservoir of microbes being deposited during the winter with slower metabolism, only to be resuspending in the spring.

Water impacts on pathogens include salinity and nutrients. Salinity has been found to negatively influence cell survival for pathogenic bacteria (Anderson et al. 2005). Nutrients such as nitrogen and phosphorus, increase in the sediment due to deposition (Scarlatos 1997). This creates a zone of increased activity in the water column.

Sediment impacts include size of parts and organic matter concentrations. Burton's study with various pathogens in freshwater sediments tested the survival times of in continuous flow chambers. *E. coli* was been found to survive in 25% fraction of clay longer than in any other type of sediment, in comparison to *Pseudomonas aeruginosa*, *Salmonella, Newport*, and *Klebsiella pneumonia* (Burton et al. 1987). This fraction of clay was in comparison to the clay, silt, and sand ratios of the river sediment and allowed *E. coli* to survive pas the 14 day study at 6 Log cfu/mL concentrations in comparison to 3 Logcfu/mL for lower percentages of clay. The study was done in completely autoclaved sediments, to minimized other interactions and predation. Garzio-Hadzick tested the particle sizes effects on deactivation, smaller particles sizes give less deactivation and decrease sensitivity to temperature (2010). The experiment found longer survival rates in sediment than water due to protection from predation. These studies overview the idea that in order for microbes to remain active they must start attached or become attached quickly to avoid deactivation due to solar radiation or predation (Hipsey et al. 2006). El Ganaoui (2007) has also proven an increase of pathogen concentration in the fluff layer, or superficial layer, of biofilms. This can be caused by higher amounts of trapped nutrients which allow pathogens to survive.

Another survival influence in stream sediments is organic matter. Haller (2009), similarly to Burton, noted that higher amounts of organic matter increased pathogenic concentration times. The survival rate in sediment was up to 50 days. The organic matter for the longer concentration times included up to 21% organic matter in comparison to other sites at 12.6% or 1.8 %. Chandran also found organic carbon content increased as the sediment survival increased, for *E. coli*, *S. paratyphi* and *V. parahaemolyticus*. Not only

bacteria but pathogens which have a much longer survival rate can be protected from predation in stream sediments.

Survival rates have also been researched in-situ experiments. Experiments on direct survival rates have found in-situ pods up to 4 months even with a 4 log die off rates (Davis et al. 2005). Jamieson (2005) found survival rates up to 6 weeks with first order decay for *E. coli*. Direct deposit manure studies found that the survival rates change over time and partition into a liquid or solid runoff state (Pachepsky et al. 2006) causing an unattached and attached fractions. LaLiberte (1982) studied *E. coli* survival and found there was a high relationship between past contamination and resuspension, due to a reservoir effect of pathogenic bacteria. Sediment can be used as an indicator of long term water bacteria concentration (Chandran et al. 2011). The history of stream sediment and flow rates can help predict pervious pathogenic concentration or pathogen build up.

Microbial Attachment

Microbial attachment is a relativity new dimension to bacterial load monitoring. Only recently have studies found a direct correlation between sediment movement and microbial movement (Sinclair et al. 2009). Microbes can be found in varying stages of attachment in sediment streams: unattached and attached. The first stage is free floating, where predation, solar radiation and other forms of deactivation results in observed exponential decay. The second stage is particle attachment, attachment is more prevalent in 3.2-4.5 micron particles with high surface area (Hipsey et al. 2006). Previous models have also found that attachment ratios are higher with smaller particle sizes (Pandey et al. 2012). Another stage is deposited unattached bacterial cells or attached cells that become dislodged, which can resuspend easily due to their small size. This stage has low concentration due to the low deposition rates of such fine particles. The last stage is the microbes that are attached and deposited at the sediment bottom. This fraction resuspends and causes an increase in the expected concentration of models.

Attachment has been found to depend on many factors, specifically environmental factors, such as extra polymeric substance (EPS) and flocs in sediment (Droppo et al. 2009). However the correlation does not apply in all situations. Nagels found boulders or large

gravel covered with EPS were not a significant source of bacterial resuspension (Nagels et al. 2002). The limitation of this study was the size of the particle outweighed the ability of the flow rate to reach critical shear stress. EPS is a very important factor in biofilm assessment and accounts for 90% of the matrix of microbial organ in streams (Karunakaran et al. 2011). In modeling Wu however didn't include the amount of *E. coli* was attached or unattached during resuspension (2009). Genetically, there are also different attachments based on the cells (Pachepsky et al. 2008). Pachepsky theorized the pathogenic and non-pathogenic *E. coli* may attach different to particles. This research will lead to genetic sequencing of specific *E. coli* cells and being able to characterize attachment by genetic information.

The effect of attachment due to the properties of the water can also be examined. Salinity decreases the survivability and the attachment therefore decreases (Anderson et al. 2005). Another effect water has on bacterial attachment is turbidity. As the turbidity increases in the water more particles are floating, which leads to higher attachment. Higher turbidity can also create a more hospitable environment by providing nutrients to be readily available.

There is disagreement in the literature regarding sediment factors effecting attachment and which factors are responsible for bacteria-particle interactions. Jamison assumed the microbial attachment remains constant after initial attachment has occurred (2004). However, Berry assumed there were two levels of attachment one weak electrostatic force and another strongly bonded electrostatic force (1991). The weak electrostatic force is more likely to remove attached microbes, while the strongly attached force is similar to Jamison's attachment. These electrostatic forces have been found to be caused by clay fractions that are often in clay bi-layers with a positive electrostatic charge on the outside, whereas bacteria walls are negatively charged. However others have suggested sand particles with the larger surface area and grooves (Pachepsky and Shelton 2011) have higher attachment. All of these factors of sediment should be investigated further.

Microbe attachment has been studied thoroughly and reported under different conditions. Hipsey (2006) found attachment ratios of up to 80% and the strongest correlation

was with the fine particles of clay. Clay percentage is highly correlated with attachment in various studies (Bai and Lung 2005; Cho et al. 2010; Dorner et al. 2006; Fries et al. 2008; Garzio-Hadzick et al. 2010; Hipsey et al. 2006; Passerat et al. 2011). Hydrology and weather events also effect attachment. Attachment during large storms has been measured at 38% over a summer season (Fries et al. 2006) . The study looked at the calculated errors for more than once cell attached to one particle and found the error to not significantly alter effect on bacterial transport. This leads us to assume a one to one cell to ratio.

Various studies have investigated the microbial attachment in the field. Soupir (2006), found attachment ratios of 53-80% in field manure application runoff and Murihead (2005) found cowpats attachment is 8% only and does not change with a rainfall event. Passerat (2011) found an attachment of 77% to suspended matter or solids during a combined sewer overflow event. Passerat was able to calculate 89% of the CSO discharge was contributed by surface water runoff which led to high volumes of water discharging. Attachment ratios are also different among different microorganism species. Krometis (2007) found 40% attachment with fecal coliforms, *E. coli* and Entercocci, 65% association with *Clostridium perfinges*, and only 13% of total coliphages. Krometis looked at storm variability and conclude the partition was similar through the storm events. Storm evens lead to the resuspension of attached particles within waterways.

Resuspension

Resuspension causes waterways to exceed maximums under TMDL regulation, due to bacteria resuspension caused by flow events from sediment bed. Bacterial transport equations can benefit from a thorough study of the resuspension in different events and sediments. *E. coli* and fecal coliform concentrations are greatest in the top centimeter of sediments and could be 100 to 1000 times higher than the bacteria concentration in the overlying water column (Pachepsky and Shelton 2011). Most watershed quality models have ignored resuspension or have assumed that it is a much smaller fraction then load from surface runoff (Je and Chang 2004). These models have not been able to accurately predict microbial loads especially after droughts followed by high flow events (Characklis et al. 2005; Davis et al. 2005; Sinclair et al. 2009; Tian et al. 2002). The rising limb of a storm has

been found to have 2 orders of magnitude *E. coli* higher concentrations after a relatively dry period (Muirhead et al. 2005; Nagels et al. 2002). Therefore resuspension should be studied for further understanding of higher concentrations of *E. coli*.

Hydrological event can cause resuspension by crossing of critical shear stress. Jamison measured the pathogen concentration in the rising limb of a storm and had the highest amounts of bacterial resuspension (2005). This interaction is due to attachment after the critical shear stress has been reached in the stream. The critical shear stress is the minimum amount of force to move a particle in a stream. It has also been found that hurricanes (Fries et al. 2006; Fries et al. 2008) are well correlated to resuspension in comparison to TSS and turbidity. Fries found that resuspension threshold was 5 mph or 2.2 m/s during hurricanes. Other sediment disturbances have also been found to correlate wave and wind to bacterial resuspension (Ge et al. 2010). Any interaction between the water column and sediments can cause resuspension including human interaction such as swimmers.

The resuspension also has much to do with the sediment which contains the microbes. The smaller particles have a lower shear stress threshold that causes resuspension. Shear stress was found to be 1.5-1.7 N/m^2 in cohesive sediments (Jamieson et al. 2005). The minimum velocity required to move sediment is a function of sediment size compaction, cohesive fractions and compaction time (Redondo et al. 2001). The sediment resuspension is also very dependent on the clays or cohesive particles within the sediment (Jamieson et al. 2005; Krishnappan 2007; van Rijn 2007; Ziegler and Nisbet 1994). Sediments also resuspend differently after multiple hydraulic events. During hydraulic events, daily loading may be months' worth of bacterial concentrations (Krometis et al. 2007). Looking at many storms, the source or storage of bacteria can be depleted over several storm periods (Jamieson et al. 2005; Muirhead et al. 2004). With the sediment beds being a repository for microbes that have settled out, it has been suggested that testing methods may be not be sampling recent *E. coli* concentrations but deposited pathogens or microbes (LaLiberte and Grimes 1982). Depositional history therefore should be taken into account while looking at the modeling resuspension.

Other factors play a role in sediment and bacterial resuspension. Stream dispersion does not seem to affect resuspension, however shear stress and entrainment coefficient have a correlation (Cho et al. 2010). Resuspension has also be modeled as directly correlated to shear stress (Collins and Rutherford 2004). Slayer showed pathogen distribution in streams has been found to be independent of salinity and temperature (Sayler et al. 1975). Resuspension can lead to higher estimates of loads and cause problems downstream when the particles again deposit. There is also a lack of information looking at the resuspension of attached and unattached particles in the literature.

Deposition

Deposition occurs to particles in floc or attached for most circumstances. It has also been found that there is a rapid decrease in microbial concentrations following a rapid storm surge (Muirhead et al. 2004). Cho found long tails after resuspension experiment (2010), in which measurements were taken after a runoff flow event into a creek. Cho measured breakthrough curves along different stations in the creek to see variations spatially and over time. The microbes being attached resuspension and becomes dislodged while in water column. Cho's conclusion also conferred the theory of microbes having relatively no settling individually. In another study, Stone (2008) proved that the higher the shear stress the lower the deposition despite biofilm stabilization. Stone showed changes in consolidation and bio-stabilization were causing a higher shear stress due to the complexity and branching of the biofilm structure. Deposition therefore can be effected by low flows and increase in suspended particles. Particles that increase deposition include flocks created or removed from biofilm structures.

Sediment Transport

Studies of resuspension are analyzed in two parts, microbes-water environment interactions and sediment-microbe interactions. Therefore it is important to understand the sediments and how experiments can be used to model similar situations. A large effect of erosion in sediments, and consequently resuspension of microbes, has been depositional history of sediment (Kim et al. 2010; Stone et al. 2008). Droppo found depositional history effected resuspension rates. The sediments deposited during a time of higher shear stress

have lower resuspension rates than those deposited under quiescent conditions (Droppo et al. 2001). Flume studies with kaolinite clay and bed sediment deposition show modeling does not take into account the bed depositional history and therefore underestimates the bed strength. Lau's experiments showed eight times the shear stress created by depositional critical shear stress (Lau and Droppo 2000). Therefore sediment depositional history should be included into studies and include them into calculations of sediment transport calculations.

Along with depositional history, particle size distribution, bio fractions, particle densities, sediment cohesion and environmental conditions factor into the sediment stabilities. Only recently have researchers looked at cohesive sediment transport (Krishnappan 2007). Research has indicated the increased clay fractions make the cohesion stronger and cannot be molded with Stoke's law or linear relationships. More complicated models have been created from experimental data (Lick 2009). However, these models focus on the cohesion caused by clay and not the biofilm aspect of the cohesion. These models are also meant for sediment, not bacterial resuspension. In this section various aspects of sediment erosion and how it relates to resuspension are discussed.

Biofilm

A biofilm is one of the most difficult substances to define. The study of biofilm is a mixture of many interrelated disciplines. Karunakaran suggests a holistic view to understand biofilm must be taken. There are many organisms that create a biofilm, including cyanobacteria, chlorophyll organisms, diatoms, and other microbes (Karunakaran et al. 2011). While investigating the cross-sections of stream biofilm Gerbersdorf, found large amounts of diatoms structures, and macrofana. The study also found that metabolic activities by microalgae, change EPS, and ionic binding sites while filling voids in sediment matrix (Gerbersdorf et al. 2008). Garcia-Aragon et al (2011) found the biofilm matrix to be made up of clay, silt, microbes, algae diatoms and EPS. It has been estimated that matrices of organic and inorganic materials may prolong the life of organisms (Droppo et al. 2009). Others have tried to quantify existence of biofilm in other ways including investigating chlorophyll a concentrations.

Finding indicators of biofilm are necessary for bio-stabilization quantification. Sutherland found chlorophyll and mucilage are both indicators of a good biofilm. The study also found the deeper sediment effected with biofilm the higher the shear stress (Sutherland et al. 1998). Friend (2003) classified biofilms and found cyanobacteria were the most prevalent type of benthic stabilizers. Biofilm is known as a type of benthic stablizied due to its cohesive nature. Investigators found that there was a positive correlation with bed stability and colloidal carbohydrates released by the biofilm organisms. A seasonal biofilm fluctuation, due to EPS formation, within the biofilm structure was also found (Friend et al. 2003). The most prevent algae was found to be cyanobacteria in older biofilm (Droppo et al. 2007). A microscopic investigation can measure the development of the biofilm by identifying and characterizing the organisms.

In streams, biofilm are characterized by the flows during development. Biofilms which develop under higher velocity conditions are often small and closely attached to the bed, whereas those developed under lower flow conditions are fluffier and less attached to the bed in mushroom shapes. Studies found biostablisation better with shorter biofilm attached to the bed. In streams the layers of biofilm grow and slough off, then are regrown in a continual cycle depending on the season and flow rates of the particular waterbody.

These biofilm structures affect the critical shear stress of sediments by increasing cohesion. Diatom structures have been found to increase critical shear stress in sediments (Paterson 1989). The biofilms are also found to change the sediment properties with increases in benthic stabilizers (Bale et al. 2006). Not only does the biofilm layer increase the cohesive strength it also creates a source of nutrient rich area in the fluff layer 3-48 times higher amounts of phosphorus in the biofilm (Kleeberg et al. 2008). Biofilms have also been grown in the lab on aquacultures on kaolin clay, where biofilm stabilization was more influential in erosion control than deposition (Droppo et al. 2001; Lau et al. 2001). Biofilm laden sediments have been tested for the organic fractions and found the organic fractions found to be 95.5% coarse sediments, and 65% for fines sediments (Koutny and Rulik 2007). There is a larger structural matrix for biofilm when there is a higher pore volume.

Studies have shown direct correlation between EPS increases and critical shear stress (Gerbersdorf et al. 2008). Droppo found testing flume biofilms, biofilm collapse occurs to make a slightly more cohesive layer called compression bed into consolidated bed. These consolidated beds have a considerably higher critical shear stress (Droppo and Amos 2001). Biofilms have been found to exist in both freshwater and marine environments. However there is a possibility to scour away the biofilm in high flow situations. Bale found turbidity caused by wave action can lower the biofilm (Bale et al. 2006). This could be due to a lack of sunlight reaching the biofilm.

Biofilms have also been researched in bench laboratory studies. Droppo (2007) tested artificially grown biofilms from natural surfaces. Droppo et al. found the critical shear is not as high as reported in other papers with artificial biofilms. Other flume tests have shown that there are differences in critical shear stress caused by biofilm loss and rips and tears of the biofilm (Droppo et al. 2007). Increase in biofilm increased the critical bed shear stress as well as decreasing the suspend solids and erosion rates. Garcia-Aragon found consolidation was less effective at changing the critical shear stress then biostabilization (Garcia-Aragon et al. 2011). Other studies have also showed that as biomass increases the mass retained in the biofilm matrix increases (Bottacin-Busolin et al. 2009). This is due to the EPS's cohesive nature which traps in particles.

Sediment Shear Stress & Resuspension Studies

There have been various studies that look at how the shear stress changes over the depth of the sediment. Researchers have analyzed sediment size with a Laser In-Situ Scattering Transmissometer (Hipsey et al. 2006). The study found correlation of fecal coliforms with 3.2 and 4.5 micron particles. Lick considered simple equations capable of modeling resuspension based on mass balance (Lick et al. 1995). Most equations take into account particle density and particle size. Rijn (2007) looked at wave action and found sand-silt particle size does not change transport as much as hypothesized, however they found salinity and water temperature make a difference in shear stress. The higher shear stresses cause more complex sediment issues including lower floc levels. Witt (2003) was able to test the resuspension changing through the water column in floods and storms events. A

major part of sediment shear stress and resuspension studies has been the idea of creating or testing samples as close to the environment as possible.

The sediment's organic matter, and microorganism's content may also impact sediment critical shear stress. It has been found that biofilms significantly increase the deposition of particles under lower shear stresses. Other studies have tried to correlate hydrodynamic transport with biofilm content, and a layer theory which states there are different layers to critical shear stress (Arnon et al. 2010). Arnon found top layer shear stress was 0.025-0.05N/m^2, and the second layer 10 times larger shear stress. The study hypothesized that the top layer is a fluff layer which is a weakly attached biofilm. El Ganaoui (2004) studied the fluff layer and found the critical shear stress was 0.025-.05 N/m^2 at three different sites. El Ganaoui also found a second brake through shear stress, which were 10 times larger which could be due to a biofilm matrix. This biofilm matrix is hypothesized to have more EPS attachment of soils filling up the void spaces and dramatically increasing the shear velocity. Droppo measured bio-stability and found erosion rates of 0.06-0.1 Pa (Droppo et al. 2007). Schaaff (2002) found fluff layer critical shear stresses to be 0.02 N/m^2 and 0.05 N/m^2. The study found nitrogen and phosphates in excess of the calculated deposition, which allows a repository of nutrients available at the bottom sediments similarly to bacteria. Nutrients have been found to increase with a decrease of inorganic material (Scarlatos 1997); this permits nutrient concentration to increase in the biofilm.

Other field studies have been conducted to investigate the resuspension in the field. Bale looked at in-situ sites with a mini flume to measure shear stress of 0.245-0.025 Pa (Bale et al. 2006). The study found shear stress was highly correlated to soil density. Bai found equations to relate suspended solids and *E. coli* concentrations that were confirmed with a model (Bai and Lung 2005). Looking at floc size as the shear stress increased the flocs grew larger up to 0.323 Pa to a limit. Another model looked at major factors on the erosion of cohesive sediment found deposition, time of consolidate, rate of application and stabilizing effects of microbes were most important (Krishnappan 2007). Muirhead's study on cow crossings was unable to find a higher concentration at crossing and the concentration were similar to the peak concentrations in the rising limb of the storm

(Muirhead et al. 2004). This showed the biofilm could resuspend and contribute to the *E. coli* concentrations measured during hydrologic events.

Bacteria Studies

Various bacterial studies have been complete investigate pathogenic resuspension. Jamison completed a study on two streams to look at survival and transport of microorganisms. Using NAR *E. coli* as tracer organisms in streams and found that there was a higher concentration in smaller particle sizes (Jamieson et al. 2005). Studies have also looked at capsulated *E. coli* in membranes keeping competitors out and measuring the deactivation time. Davis found in the capsules *E. coli* lasted up to 75 days in Karst springs (Davis et al. 2005). Long term studies have also found *E. coli* strains in creek after introduction of NAR 1-3 weeks after inoculation (Jamieson et al. 2005). Detection of *E. coli* is effected by different factors.

A study by Murihead used traceable NAR *E. coli* for bacterial transport studies. They measured the background concentration of *E. coil* during a storm and found a difference of two orders of magnitude in comparison to regular stream flow. The amount of bacterial storage is not infinite and subsequent storms a decrease was observed in the peak bacterial concentration (Muirhead et al. 2004). Other studies have shown increase in biofilm was well correlated to deposition. Arnon observed an increase in particle retention with an increase in particle size and EPS concentration (Arnon et al. 2010).

Resuspension Models

There are various models for resuspension of sediments in the literature. Most models have incorporated at some point Stokes law, mass balances, kinetics, diffusion, sediment properties and water properties (Rehmann and Soupir 2009; Tian et al. 2002). Some models have incorporated temperature, pH, DO, solar radiation, nutrients, and turbidity-flux of organisms. Tian (2002) considered the spatial and temporal variation of sources and assumed a resuspension of 7% daily flow volumes per year. This is a constant rate instead of value calculated through a means of flow rates, or critical shear stresses. In comparison Hipsey's model was able to determine temporal and spatial variability which

emphasized different rates of mortality, growth and sedimentation (Hipsey et al. 2008). Models have looked at various ways of incorporating the resuspension of sediment and microbe attached concentration into water quality models.

It has been difficult to incorporate point and non-point sources into water quality models. Some models have been able to separate point and non-point sources (Petersen et al. 2009). Peterson, was able to calculate the amount of reductions required to meet TMDL's using an excel model and assumed a steady resuspension load. Soil and water assessment tool (SWAT) is a widely used model for waterbody and water quality modeling. However, SWAT does not include the resuspension of fecal materials (Neitsch et al. 2005). Although there are many models none of them have truly incorporated the attachment and resuspension traits crucial to bacterial transport (Benham et al. 2006). Beham noted the SWAT model was used to assess bacterial concentrations and simplified the model to be a mass flux without resuspension. SWAT did include bacterial survival that was completely dependent on temperature. Researchers are looking at the sediment and water column interactions and how they affect resuspension.

While new models are starting to include resuspension previous versions generally ignored resuspension. Wilkinson ignored resuspension from the sediments and its effect on load (Wilkinson et al. 1995). Wikinson's model investigated channel storage of fecal coliforms and flow was correlated to higher coliform counts. Other studies have specified resuspension loads independent of flow, and sediment properties (Petersen et al. 2009). In these cases most models specify attachment ratios and assume a bacterial load. Russo (2011) modeled attached resuspension and found a good correlation to bed and critical shear stress. The authors carefully to look at the silt and clay fractions, densities, settling velocities, critical shear for deposition, critical shear, erodibility factor, fecal coliform parameters, portioning, decay rate, suspended solids associated decay rate, and bed-sediment associated decay rate. Using these parameters Russo concluded during high flow events resuspension was a much smaller fraction of the overall concentration (Russo et al. 2011). Other models have also specified resuspension based on the shear stress (Sanders et al. 2005) and investigated the tidal effects on total coliforms, *E. coli* and Enterococci. Sanders measured concentration of pathogens in various costal sediments.

Sediment concentrations play a large role in resuspension calculations. Wu (2009) used a resuspension value proportional to flow rate and *E. coli* concentrations in sediments. However, Wu found no correlation with particle size or sediment bacterial concentration (2009). Kim modeled resuspension with SWAT and modified SWAT to include resuspension and deposition (2010). Kim (2010) identified issues with high *E. coli* runoff and underestimated the persistence in stream, this was probably due to the lack of loading from calculated resuspension. Cho correlated turbidity to resuspension of *E. coli* (2010). Another way to correlate resuspension is through turbidity of water by assuming a ratio of attached *E. coli* concentration within the sediment. Another method of calculating resuspension is to assume it is proportional to the concentration in the sediment (Sanders et al. 2005). The concentration is dependent on historical loading of the stream to achieve a more accurate concentration.

Along with SWAT and Excel used to calculate resuspension, Droner used WATFlood to estimate resuspension at equal or greater values for land based sources (2006). The study showed correlation between land application and large loads during after the first rain, assuming complete deposition due to tile flow. Bai assumed linear to model incorporate attached bacteria in Environmental Fluid Dynamics code model. The study didn't consider the different distributions of the bacteria and assumed a uniform layer (Bai and Lung 2005), which simplifies the model. However, this assumption causes limitations of application to a stream bed.

Other models were more particular about incorporating the sediment properties, such as cohesion. It has been shown that as particle size decrease cohesion becomes dominate (Pandey et al. 2012). Lick suggested a sediment resuspension model based on cohesive and non-cohesive properties. He related non cohesive shear stress directly to the size of the particles through experimental data (Lick 2009). A model developed by Ziegler was found to accurately predict resuspension of cohesive and non-cohesive particles (Ziegler and Nisbet 1994). Ziegler was able to model flooding situations and sediment concentrations. Flooding situations often provide the best contrast of data to compare with quiescent conditions. Being able to compare increase in flow rate is critical.

Larger scale model tests have also been completed in the field. Pachepsky modeled bacterial transport and survival at different scales including pedon, hillslopes and watersheds. He found that there were different fitting factors and different release rates over time (Pachepsky et al. 2006). Factors included survival, attachment, and transport. Attachment coefficient was related to percentage of clay particles and threshold of resuspension per volume of flow. Hipsey also modeled resuspension as a function of flow (Hipsey et al. 2008). Jamieson choose to model equations of concentration based on the fractions of *E. coli* in coarse or fine sediments and called for better understanding of the FC associated with particles better (Jamieson et al. 2005). The modeling parameters needed are factors including attachment and concentration of pathogens in sediments. These parameters will be used to calculate the flux of pathogens being resuspended into the water column.

Future

Many of the studies looked at in this review have mentioned how little data has been collected. There are variations of the attachment ratios and which are not fully understood due to the variable sensitivity. No studies on resuspension and attachment fractions have been completed for microbial concentrations. These studies can be based on sediment studies and compared or modified to meet the future need (Rehmann and Soupir 2009). No comparison studies of different attachment and resuspension rates with different river bottom sediments have been completed. This is a major issue when looking at attachment rates which relate to the resumption rates in waterways with different bottom sediments.

Water column sampling does not tell the whole history of the sediment behavior. Droppo calls for sampling methods to change due to sediment concentrations being a major source of the load (Droppo et al. 2009) not only in the water column. This would make it easier to model the water quality before flooding events in order to provide warnings to recreational users. Care should be taken to investigate pathogen concentration in high use recreation areas and food production waters (LaLiberte and Grimes 1982). This direct contract of high concentrations of pathogens should be limited and therefor prevention is a major issue.

Other improvements in the future of water quality can be achieved in preventative care and faster detection of pathogens. The sources of pollutants should be limited by allowing riparian buffers between streams which limit the velocity of runoff and adding microbial disinfection treatment such as UV into Waste Water Treatment Plants (Ouattara et al. 2011). Only by limiting the sources of pollutants will we be able to control the resuspension effects. Detection is also a big part of improving the water quality. Detection of *E. coli* can be done through membrane filtration but this method often takes longer than the threat is prevalent. Although this method takes 24 hours, it is cost effective and well known. Pathogens should quickly and effectively be reported to those who will be affected.

Chapter 3: Resuspension of *E. coli* from Stream Bottom Sediments

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Abstract

Microorganisms in streams are potentially transported as freely suspended organisms or attached to particulates. Many water quality models currently neglect resuspension, an important process to predict in-stream bacteria concentrations. The objective of this work is to measure resuspension of *E. coli* from different bottom sediments under a range of flows. An assessment of the attached fraction and resuspension rate was completed by measuring *E. coli* concentrations in a recirculating flume at two locations. The test was completed for three different bottom sediments: sand, sand-silt, and sand-silt overlain with biofilm. The experiments were conducted at flows below and above the calculated critical shear stress, as well as two different water depths. Attachment ratios were assessed using a combination of filtration techniques. Attachment ratios increased as particle sizes decreased and percent of attached *E. coli* generally decreased after the critical shear stress was surpassed. Statistical analysis found that both bottom sediments and flow rate impact attachment of *E. coli*. The calculated unattached *E. coli* resuspension rates from the different bottom sediments were 1.32E-6 cfu/m^2/s for sand, 1.03E-6 cfu/m^2/s for sand-silt, and 1.78E-6 cfu/m^2/s for biofilm. The calculated attached *E. coli* resuspension rates were 3.84E-6 cfu/m^2/s for sand, -2.84E-6 cfu/m^2/s for sand-silt, and -8.06E-6 cfu/m^2/s for biofilm. Statistical analysis found that bottom sediments and flow rate impact total *E. coli* resuspension, attached *E. coli* resuspension, and unattached *E. coli* resuspension. The model, calibrated using the calculated resuspension values, was able to accurately represent both attached (r^2= 0.91) and unattached (r^2= 0.85) *E. coli* resuspension. This work increases knowledge and ability to

track particles in different environments, by separating unattached and attached resuspension. It is possible to model attached resuspension with sediment resuspension equations. The risk of unattached fraction of *E. coli* resuspension still needs further assessment. These equations should be applied to data collected in the field where turbulent flow may affect the resuspension of various bottom sediments.

Introduction

The presence of pathogenic organisms in waters has compromised water quality and poses a risk to human health. While many pathogen impaired waters are rivers or coastal waters, pathogen contamination of public beaches is especially concerning because children or immunocompromised individuals could come in contact with infectious microorganisms. Pathogens can be harmful through contact with contaminated waters by becoming ingested or entering via open wounds. Various studies have found that fecal contamination leads to illness among swimmers (Marion et al. 2010; Sinigalliano et al. 2010; Wade et al. 2010). The volume of water ingested during recreational activities was found to be 4 mL in comparison to 10 mL during swimming activities (Dorevitch et al. 2011). Infectious dose of *E. coli* can be anywhere from 10 to 100 cfu/100mL, and the EPA single sample maximum standard for *E. coli* for contact recreation is 235 cfu/100mL. An estimated 120 million cases of gastrointestinal illness are caused by bathing in polluted coastal waters (Shuval 2003). Pruss (1998) found that in both fresh and marine waters increased risk of gastrointestinal illness (GI) systems was found from few cfu/100mL to 30 cfu/100mL. Due to the increasing scarcity of fresh water, protecting water resource has become an international goal. One of the United Nations millennium goals includes access to safe drinking water (Scachs 2005), and for that goal to be met accurate models of pathogens in aquatic environments must be provided.

Pathogens can enter waterways through both point and non-point sources. Point sources include wastewater treatment plants and stormwater outfalls, while non-point sources include runoff from agricultural lands receiving manure application, grazing cattle allowed direct access to streams, leaking rural septic systems, and wildlife. Pathogen contamination from non-point sources is difficult to quantify. After bacteria enter water

bodies they settle into bottom stream bottom sediments or remain freely suspended and are transported downstream.

Previous studies have determined that the percentage of microbial attachment in streams ranges from 8-80% (Fries et al. 2008; Krometis et al. 2007; Muirhead et al. 2005; Pachepsky et al. 2006). Higher attachment is observed to increase with an increase in surface area and larger concentration (Hipsey et al. 2006). The percent attached is influenced by the clay fraction, organic material, and particle surface area (Bai and Lung 2005; Cho et al. 2010; Dorner et al. 2006; Fries et al. 2008; Garzio-Hadzick et al. 2010; Hipsey et al. 2006; Pachepsky and Shelton 2011; Passerat et al. 2011). Investigations have also shown differing levels of attachment due to weak electrostatic forces and adsorbed particles (Berry 1991). The attachment to particles changes in-stream transport behavior of microorganisms, leading to greater deposition, which is not normally associated with free floating, buoyant bacteria. These attached microorganisms deposit in the stream sediments and are sheltered by their environment from deactivation from sunlight or predation. Pathogens that settle into bottom sediments are shielded from natural predators, and therefore the microorganisms are able to persist and potentially remain virulent for longer periods of time (Burton et al. 1987; Haller et al. 2009; Jamieson et al. 2005). The sediment bed environment also provides nutrients to sustain and in some cases promote growth. After settling into bottom sediments, bacteria may attach to particles to increase survival (Garzio-Hadzick et al. 2010). The surviving and possibly multiplying pathogens can then act as a source to water column through resuspension (Droppo et al. 2009; Haller et al. 2009), especially after periods of low flow.

Biofilms have also been found to impact in-stream microbial transport through attachment and increasing critical shear stress (Droppo et al. 2007; Garcia-Aragon et al. 2011; Sutherland et al. 1998). Biofilm growth provides a matrix which stabilizes the sediments of streams and includes a variety of organisms, such as cyanobacteria, chlorophyllic organisms, diatoms and other microbes (Karunakaran et al. 2011). The extracellular polymeric substances (EPS) are made up of mucilage or proteins released by the biofilm. The EPS concentration is very important in attachment (Droppo 2009) although not always correlated (Nagels et al. 2002). Nagels found the size of particles, such as

boulders and gravel, can outweigh the effects biofilm factors. Factors in the stream impacting resuspension of bacteria from bottom sediments to the water column include bottom sediments type and the presence of biofilm. Biostabilization caused by biofilms and EPS has been shown to increase the critical shear stress (Droppo 2009; Friend et al. 2003; Sutherland et al. 1998). The biofilm along with increasing the shear stress of the sediment are found to create an environment of nutrient rich area in the biofilm 3-48 times larger than in the water column (Kleeberg et al. 2008).

Once pathogens are attached to bottom sediments in the sediment bed, particle-associated pathogens can resuspend during high flow events (Characklis et al. 2005; Davis et al. 2005; Sinclair et al. 2009). These resuspension events may contribute to the overall pathogen load to the stream, leading to exceeded water quality standards. Fecal coliform and *E. coli* concentrations are greatest in the top centimeter of stream sediments, and have been found to be up to 3 orders of magnitude higher than the bacteria concentration in the overlaying waters (Pachepsky and Shelton 2011). The highest *E. coli* concentrations have been observed during the rising limb of the storm hydrograph (Jamieson et al. 2005), likely due to resuspension of persistent organisms. As available bacteria in bottom sediments are depleted, contributions to the water column decrease (Jamieson et al. 2005; Muirhead et al. 2004). Microbial resuspension has also been observed during hurricanes and turbulent wave events due to high winds (Fries et al. 2006; Fries et al. 2008; Ge et al. 2010). Water quality models often ignore the bacteria resuspension process (Petersen et al. 2009), which leads to underestimation of concentrations during high flow storm events and over estimation during lower flows due to attachment, deposition and resuspension. While some models include resuspension other models ignored resuspension such as Wilkinson's (1995) model ignored resuspension from the sediments and its effect on load.

Other models have incorporated resuspension into their water quality models. Tian (2002) considered spatial and temporal effects on resuspension and assumed 7% daily flow volumes per year. Some studies have specified resuspension independent of flow and sediment properties (Petersen et al. 2009), while others specify resuspension based on shear stress (Sanders et al. 2005). Hipsey related resuspension as a function of flow rate (Hipsey et al. 2008). Soil and water assessment tool (SWAT) is a widely used model for waterbody

and water quality modeling. However, SWAT does not include the resuspension of fecal materials (Neitsch et al. 2005). Kim (2010) modified resuspension with SWAT to include resumption and deposition. However, this model had issues with underestimating the persistence in a stream. Lick (2009) suggested using cohesive shear stress and non-cohesive shear stress directly to the size of the sediment particles based on experimental data. Pandey (2012) has developed a model based on sediment erosion, from Lick, for attached resuspension using shear stress and sediment properties. However, this model does not look at unattached erosion rate in various bottom sediments. This lack of equations to model both attached and unattached fractions of resuspension cause impairments in the water ways.

The U.S. EPA has identified pathogens as the leading cause of water quality impairments (USEPA 2010). The U.S. uses the Total Maximum Daily Load (TMDL) program to set limits on pollutant loads and recommend measures to improve water quality. The cost of implementing TMDLs is estimated between 1 and 3.4 billion dollars annually (USEPA 2002). The cost of implementation includes modeling the concentrations for various storms and flow conditions. These models often ignore the effect of pathogens in sediment beds which can be resuspended. Other studies have looked at attachment in field studies and tried to model resuspension as a value or a proportional value to the flow rate. Most of these studies have been completed in the field and not many have looked at the effects of attachment and resuspension in a flume setting. Despite the previous work on this topic, a study measuring attachment and resuspension rates as a function of bottom sediments and flow is lacking. The goal of this study was to improve understanding of how different bottom sediments impact in-stream bacterial resuspension and attachment. The objectives were to measure the *E. coli* attachment ratios in simulated flows over three different bottom sediments, flows, and two water depths to characterize bacteria resuspension. The hypothesis of this first goal is that the increased flow rates will increase bacterial attachment and resuspension. The second goal of this study was to predict resuspension of attached and unattached *E. coli* as a function of flow and bottom sediments. The hypothesis of the model is that different bottom sediments and depths will provide different variables for modeling resuspension. The results of this study will improve understanding of *E. coli* attachment to particles and resuspension rates which could be

incorporated into water quality models, improving the prediction of pollutant sources for load allocations in watershed management plans.

Materials and Methods

The experiment was designed to test two segments of a recirculating flume for *E. coli* concentration and resuspension. Data collection was performed at the indoor flume and samples were transported to the water quality laboratory to be analyzed for *E. coli* concentrations. Using the collected data the attached and unattached resuspension were calculated. Calculated values were compared to segment a model for predicting resuspension using a recent approach proposed by Pandey et al. (2012), which uses modified sediment Equations developed by Lick (2009). The Equations were modified using the calculated resuspension from the resuspension experiments conducted. The model was parameterized for different bottom sediments as well as for unattached and attached bacteria resuspension.

Resuspension Experiments

Experiments were designed to assess the attached fraction and resuspension rate of *E. coli* in a recirculating flume at two locations, 4.88m (location 1) and 7.32m (location 2) downstream of the flume inlet shown in Figure 1. The test was completed for three different bottom sediments: sand, sand-silt, and sand-silt overlain with biofilm. The experiments were conducted at flows below and above the calculated critical shear stress, as well as two different water depths which averaged 15 cm and 18 cm over all experiments, as described in Table 1. All experiments were conducted under steady state flow

Table 1 Overview of Experiment Setup

Sediment	Depth (cm)	Q (m3/s)	Time Periods Tested (min)	Type of flow rate
Biofilm	16	12.60E-03	0, 15, 30, 45, 60	L
Biofilm	15	14.20E-03	0, 15, 30, 45, 60	M
Biofilm	15	14.60E-03	0, 15, 30, 45, 60	M
Biofilm	23	14.50E-03	0, 15, 30, 45, 60	M
Biofilm	16	16.10E-03	0, 15, 30, 45, 60	H
Sand	16	4.45E-03	0, 15, 30, 45, 60	L
Sand	16	5.09E-03	0, 15, 30, 45, 60	M
Sand	22	4.56E-03	0, 15, 30, 45, 60	M
Sand	15	10.40E-03	0, 15, 30, 45, 60	H
Sand-Silt	16	1.56E-03	0, 15, 30, 45, 60	L
Sand-Silt	14	2.45E-03	0, 15, 30, 45, 60	M
Sand-Silt	24	3.14E-03	0, 15, 30, 45, 60	M
Sand-Silt	15	5.44E-03	0, 15, 30, 45, 60	H

conditions and water samples were collected at 15 minute increments.

The experiments were conducted in a recirculating plexiglass flume (Engineering Laboratory Design, Inc., Lake City, MN). The flume was 9.1 m long, 0.6 m wide and 0.6 m deep (Figure 1). The slope on the flume could be adjusted five percent and for these experiments was set constant at one percent. Water was drawn from a sump by a combination of pumps with capacities of 500 and 300 gpm. These pumps were used in combination with butterfly valves to achieve the desired flow rates. From a 21.24 m^3 sump, water was pumped to a head tank and then flowed gravimetrically through a flume distribution line for constant flow. The flume was fitted with a flow straightener at 0.3 m to create steady and laminar flow for all experiments. The flow straighter is a 0.61 m square made out of plastic tubes, making a honeycomb, which allow the water to pass through them while removing the wave actions created by air bubbles. A weir was installed downstream of the flume, to remove bottom sediments from the system. The weir had four sections that could be increased at 0.15m intervals, achieving maximum depth of 0.6 m. All water samples were collected after steady state had been reached.

The experiments were repeated for three different bottom sediments: sand, sand-silt

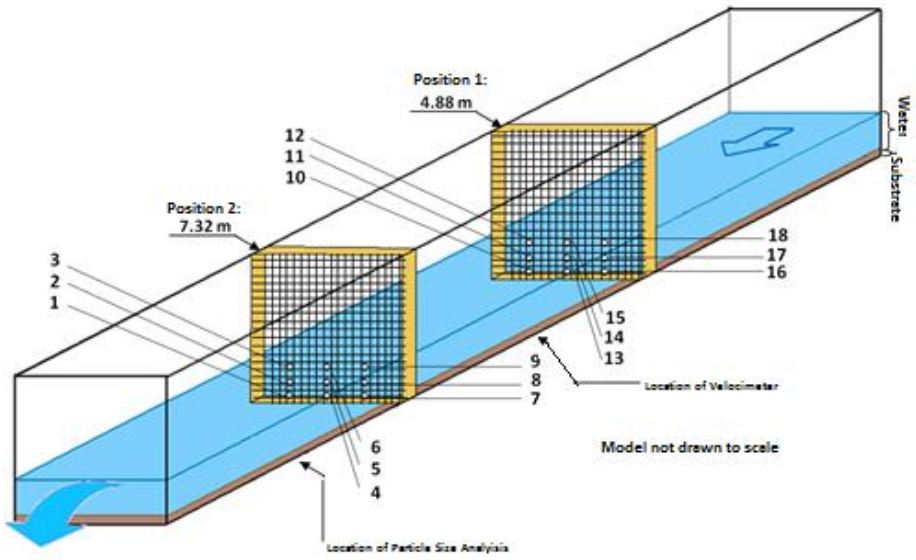

Figure 1 Flume sampling at two locations and 18 points total, nine per sampling location. Bottom sediments was inoculated from 0 to 7.32 m. The 3.0 cm of bottom sediments was changed for each set of the experiments.

and sand-silt-biofilm. The sand was 149-400 µm diameter quartz (Hallett Material, Des Moines, Iowa). The silt was less than 44 µm diameter, 350 mesh, quartz (Agsco Corp, Wheeling, Illinois). The sand-silt mixture was made by mixing equal quantities by mass of each material. The depth of the bottom sediments bed was set at 3 cm following the work of others (Chapra 1997; Droppo 2009; Haller et al. 2009). The water was also supplemented with nutrients including nitrogen and phosphorus to match concentrations of 0.5 mg/L and 2.5 mg/L, respectively, as observed in a local Iowa stream, Squaw Creek (P.K. Pandey, personal communication). The nutrient supplement was ground and autoclaved at 121^{o}C for 20 minutes to remove impurities before being added to the sump. These background nutrients were set at three times the background concentration for the growth of the biofilm. To dechlorinate the water, water from the City of Ames, Iowa was treated with stress coat (MARS Fish Care, North America) by adding 0.17 mL/L stress coat per liter of water (McDaniel et al., under revision).

The seed material for the biofilm experiments was the first centimeter of stream biofilm collected from Squaw Creek, near Ames, Iowa. Once the seed sample was collected it was filtered to remove the coarse sediments using a wire 60 mesh sieve. Biofilm or the fluff layer has been described previously (El Ganaoui et al. 2007; Kleeberg et al. 2008; Schaaff et al. 2006) as a community of benthic stabilizers found in stream bottom sediments. A biofilm layer study was included to examine the effects of biostabilization on resuspension and *E. coli* association with particles. The biofilm was grown on the bottom sediments in the flume following the procedure described by Droppo (2009), in this procedure sediment was deposited under quiescent conditions from 1-3 cm. Grow lights were then used to develop biofilm for 12 hours of light and 12 h of darkness. The flow of the flume during development of the biofilm was set between 1 and 5 cm/s (9.28E-4 and 4.64E-3 m^3/s). The biofilm was grown for 30 days with a nutrient supplement added weekly. Between experiments the biofilm was allowed to recover for one week. The biofilm population was sampled after the 30 days to ensure a sufficiently diverse environment. The samples were examined by the use of a bright field microscope Zeiss Axioplan II (Carl Zeiss Microscopy, LLC, Thornwood, NY 1) to ensure the population of diatoms, blue green algae and protozoa were representative of field conditions. The biofilm had reached maturity and evenly covered was confirmation using microscopy. After each run for sand and sand-silt

bottom sediments, the water was drained and rinsed at least three times between runs to remove any residual *E. coli*. This allowed chlorinated water to clean the system, including the bottom sediments, between the runs. For the biofilm experiments, the water was emptied once from the tank between each run; however, the biofilm in the flume was not rinsed at the same flow rates, so that the biofilm remained intact. The bottom sediments were completely removed between each change of bottom sediments type in the experiments. During the removal process the flume was shocked with a chlorine booster pack, power powder plus (Leslie's Swimming Pool Supplies, Phoenix, AZ) and run for a minimum of 6 hours.

Experiment Procedure

Prior to each run, the shear stress was calculated using diameter based equations for non-cohesive bottom sediments proposed by Lick (Lick 2009). Using the calculated shear stress, the velocity was back calculated with Manning's Equation and bed shear stress as described previously (Jamieson et al. 2005). Each set of experiments for each bottom sediments were designed to include two or three flows below the critical shear stress and one flow above the critical shear stress, all at a water depth ranging between 15cm. For all bottom sediments, one experiment was completed at a stream depth of 23 cm with similar flow rate as a test under the critical shear stress. The shear stress values calculated for the sand, sand-silt, and biofilm bottom sediments were 2.5E-1, 1.8E-2 and 1.3 N/m^2, respectively. The biofilm shear stress was calculated by averaging the two types of bottom sediments due to the shear equations being completely dependent on the mean diameter of the sediment. After calculating the shear stress, it was increased by an order of magnitude as previously described by El Ganaoui et al (2004). The calculated shear stress was used to set the experimental flow rates. The flow rate in which the critical shear stress was surpassed was performed last in the experiments.

An Acoustic Doppler Velocimeter (ADV) (Norteck Inc., Vertrono Cable Probe P22596) was used to collect and set the flow in the flume. For setting the flow in the flume, the probe was set at location 2 from the inlet and six cm above the bottom of the flume, and was averaged over a three minutes sample period. Additionally, a ten point profile was

collected in ten intervals from the bottom sediments to the top of the water at 7.32 m from the top of the water to the bottom bottom sediments. The ten point profile was used to calculate a more accurate flow rate after the initial velocity was set. The velocity was also measured at each point where samples were collected to flow-weight the samples.

Once the water depth and velocity were set, the pump was turned off so that the bottom sediments could be inoculated with *E. coli*. A sediment sample was collected before inoculation test for any *E. coli* remaining in the sediment from the previous experiment. Environmental strains of *E. coli* were collected and grown in Trypticase Soy broth (Becton, Dickinson and Company, Sparks, MD) to the stationary phase of the growth curve, approximately 10-14 hours in a 45 ^{o}C water bath. The *E. coli* concentrations in the tryptic soy broth inoculum ranged between 5.3E10 and 2.4E14 cfu/100mL, resulting in an application of 2.65E11 to 1.2E15 cfu being applied to the bottom sediments. The *E. coli* solution was sprayed onto each bottom sediment: For the sand and sand-silt experiments the top centimeter of bottom sediments was mixed, but for the biofilm experiments the bottom sediments was not mixed or disturbed. After inoculation the flow was increased to the specified rate until steady state was reached, approximately ten minutes. The *E. coli* concentration of the water was tested before and after inoculation.

Data was collected at two locations along the flume, 4.88 m (location 1) and 7.32 m (location 2) from the water inlet (Figure 1), every fifteen minutes for one hour. Grab samples were also collected at the flume's inlet, at 0 m, at each time period to determine background *E. coli* concentrations in the inflow. Water collection points were located at location 1 and location 2 downstream from the entrance of the flume (Figure 1). At each collection point 9 samples were collected in a grid pattern evenly distributed at 0.15 m, 0.30 m and 0.45 m along the cross section of the flume. Along the depth of the water the collection points were evenly distributed along the depth of the flume. The samples were collected using 1.27 cm diameter, and 1.83 m long sterile vinyl tubing and were replaced between each experiment. After being placed the tubing was inserted into wire mesh, 1.27 cm squares, placed on a pine 0.61 m square frame. Before each sampling event the sample collection tubes were opened and allowed to flow for thirty seconds to rinse the line of any water from the previous sampling event. The tubing was filled using a peristaltic pump and

sealed with pinching clamps. Samples were collected for all points at five time intervals at 0.5 min, 15 min, 30 min, 45 min and 60 min. The samples were collected in sterile 1000 mL bottles. The flow weighted values were obtained and averaged for each point concentration in order to achieve the averaged concentrations listed.

After the runs were completed, all samples were transported on ice to the water quality research laboratory on the ISU campus. The samples were filtered using standard membrane filtration techniques (APHA. 1998) and a 0.45 micron filter (Millipore, Billerica, MA) within 24 hours. Filters were placed on modified mTEC agar (USEPA 2000) and incubated in a water bath for 24 hours at 35 °C. The samples along with the measured flow at each collection point were used to compile samples into velocity weighted samples which were analyzed for the total concentration of *E. coli* as well as the concentration associated with particles. The separation technique was developed using procedures described previously by McDaniel (2011). To measure the attached fraction, each sample was shaken gently and split into two 100 mL bottles. One set of bottles was shaken at 400 rpm for ten minutes in an orbital shaker, while the other set was filtered through an 8 micron filter to remove attached particles. The filtered water and the shaken composite samples were processed using standard membrane filtration as described above. By measuring the total and the unattached concentrations, the attached concentrations were calculated using a mass balance approach.

Bottom sediments samples were collected before and after the inoculation to assess the concentration of *E. coli* in the bottom sediments. Bottom sediments samples were analyzed using equal parts of phosphate buffer water (HACH Company, Loveland, Colorado) and bottom sediments by mass. The samples were then stirred using magnetic stir bars for ten minutes to disperse the *E. coli.* The supernatant of the slurry was processed by membrane filtration techniques.

All samples were analyzed for turbidity including each point sample, composite samples, and background samples using a Hach 2100N Turbidimeter (HACH Company, Loveland, Colorado). Samples of suspended particle were analyzed at the second collection site. Using a nine point grid, as shown in Figure 1, and a ten point profile evenly distributed

from the top of the water column to the bottom sediments. The profiles were compiled using a Laser In Situ Scattering and Transmissometry (LISST) (Sequoia Scientific, Inc., LISST-100x-Type C) device, which measures between 2.5-500 micrometers.

Data Analysis

Critical shear stress was calculated as expressed by Lick (2009).

$$\tau_{cn} = 0.414 \times 10^3 \times d \quad (1)$$

Where τ_c is critical shear stress in units of N/m^2, d is the diameter in m. These shear stress calculations combined with the bed shear equation by Jamieson (2005), allowed a preliminary critical flow rate to be calculated and set for the experiments.

$$\tau_{cn} = yS^{1/4}Q^{3/2}\left(\frac{n}{A}\right)^{3/2} \quad (2)$$

Where y is specific weight of water (N/m^3), S is slope, Q is flow rate (m^3/s), n is the Manning's roughness coefficient, and A is cross sectional area of flow (m^2). This flow rate was revaluated using the ten point cross-sectional profile for the flume.

After the attached and unattached percentages were determined, the resuspension was calculated from the flow, particle surface area and *E. coli* concentration in the water. The resuspension rate calculation was modified from Jamison et al (2005) by changing the parameter representing the average concentration of *E. coli*. Here, the average value was substituted with the difference concentration for the specified area by using mass balance (Figure2).

$$R_{ac} = (C_a - C_{ao}) \times 10^6 \times \frac{Q}{SA} \quad (3)$$

$$R_{uc} = (C_u - C_{uo}) \times 10^6 \times \frac{Q}{SA} \quad (4)$$

Where R_{ac} is the calculated attached resuspension rate ($cfu/m^2/s$), C_a is the attached concentration (cfu/100mL) in the water column, C_{ao} is the attached concentration (cfu/100mL) in the water column coming through the inlet at a specific time, C_u is the

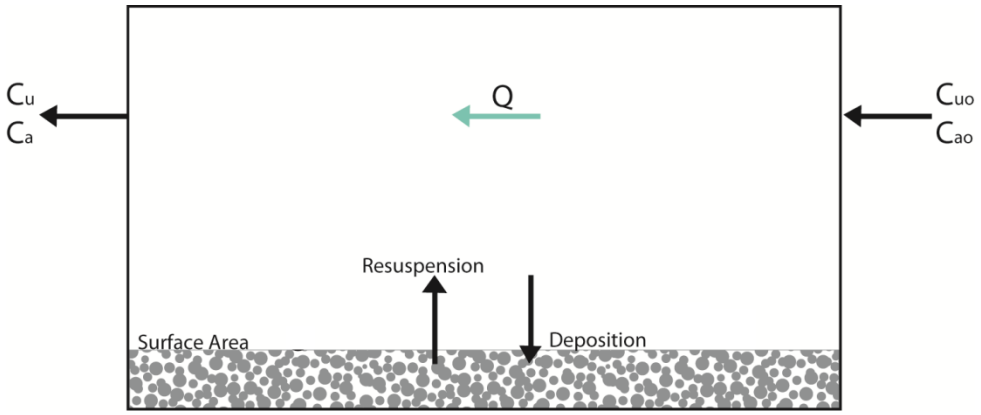

Figure 2 Mass Balance for Calculated Resuspension Equations

unattached concentration in the water column (cfu/100mL) at a specific time, C_{uo} is the attached concentration (cfu/100mL) in the water column coming through the inlet Q is the measured flow rate (m^3/s) and SA is the surface area(m^2). Where the bottom sediments area is contributing to resuspension between the two collection location, and 10^6 is a conversion factor. The total resuspension was found by adding the unattached and attached resuspension.

Statistical Analysis System (SAS) software version 9.2 (SAS Institute Inc., Cary, NC, USA.) was used to perform a Pearson's correlation analysis using the proc corr procedure to investigate potential relationships between parameters for each bottom sediments. Within each bottom sediments and when the water depth was set at 15 cm a correlation was completed; it examined relationships between flow, turbidity, location, *E. coli* percent attachment, *E. coli* unattached resuspension rate, *E. coli* attached resuspension rate, *E. coli* concentration, and mean particle size. Within each bottom sediments the same parameters were also analyzed across the two water depths with the similar flow rates, however this comparison included depth as a parameter instead of flow rates.

Using the proc glm (generalized linear model) procedure in SAS, an analysis of variance (ANOVA) and lsmeans with an adjusted Tukey's pairwise procedure was completed to investigate the potential effects between parameters. When the water depth was set at 15 cm, a two way ANOVA was completed for the bottom sediments, flow rate and bottom sediments-flow rate interactions on mean particle size, turbidity, *E. coli* percent attachment, *E. coli* unattached resuspension rate, *E. coli* attached resuspension rate and total

E. coli resuspension rate. A two way ANOVA was completed for the effects of *E. coli* sediment concentration and bottom sediments impacts on *E. coli* water background concentrations. Another two way ANOVA was completed for the effects of *E. coli* attachment concentration and bottom sediments impacting turbidity. A two way ANOVA was completed for the effects of turbidity and bottom sediments impacting total resuspension. A two way ANOVA was also completed *E. coli* water column concentration and bottom sediments impacting total resuspension.

Within each bottom sediments a two way ANOVA and lsmean was completed on two water depths with the similar flow rates, using the bottom sediments, water depths and bottom sediments-water depth interactions. The tests were completed on the mean particle size, turbidity, *E. coli* percent attachment, *E. coli* unattached resuspension rate, *E. coli* attached resuspension rate and total *E. coli* resuspension rate.

ANOVA and lsmeans were also completed by dates in order to test for variations of parameters in time. At a singular depth the relationships were examined for *E. coli* unattached concentration, *E. coli* attached concentration, *E. coli* unattached resuspension rate, *E. coli* attached resuspension rate and total *E. coli* resuspension rate. The calibrated resuspension model analysis was completed using the least squares regression line for comparing attached and unattached *E. coli* resuspension. The regression was completed for the uncalibrated model in comparison to the calculated resuspension; secondly the regression model was completed for the calibrated model in comparison to the calculated resuspension. For all statistical tests significance was set at P-value < 0.05.

Predicting Resuspension

Similar to Pandey (2012), modified sediment resuspension equations were used to predict attached and unattached resuspension for different sediments and flows. The following equations were developed by Lick (2009), using experimental data in which erosion rate was determined by the erosion rate at the threshold of erosion and shear stress. In order to estimate resuspension Pandey (2012) multiplied erosion equations developed by Lick by the concentration of attached *E. coli* in the sediments (Equation 5). Similarly,

Lick's Equation (6) for smaller than 432 microns to predict resuspension of unattached *E. coli*; Where $\tau_b > \tau_{cn}$ in order not have negative numbers.

$$R_a = C_{ab} \times E_{ao} \left(\frac{\tau_b - \tau_{cn}}{\tau_c - \tau_{cn}} \right)^{n_a} \quad (5)$$

$$R_u = C_{ub} \times E_{uo} \left(\frac{\tau_b}{\tau_c} \right)^{n_u} \quad (6)$$

Where R_a is the resuspension rate of attached *E. coli* (cfu/m^2/s), R_u is the resuspension rate of unattached *E. coli* (cfu/m^2/s), E_{oa} is the erosion rate at the threshold of erosion of attached sediment and *E. coli* (m/s), E_{ou} is the erosion rate at threshold of erosion of unattached *E. coli* (m/s), τ_b is the bottom shear stress, τ_{cn} is the critical shear stress for non-cohesive sediments (N/m^2), τ_c is the critical shear stress for cohesive sediments (N/m^2), C_{ab} is the concentration in the sediment of attached *E. coli* (cfu/m^3), C_{ub} is the concentrations of unattached *E. coli* in the sediment bed (cfu/m^3), n_a is the exponent of attached particles, and n_u is the exponent of unattached particles. The exponents, n_a and n_u, were found by lick to be approximately equal to two, and is considered a fitting parameter. Critical shear stress for cohesive sediments, E_{ao}, is set at10^{-6} m/s to represent the erosion rate at the threshold of erosion as described by Lick (2009). Lick calibrated the n_a exponent to be equal to two for small and intermediate particles using field data. As described previously by Pandey et al. (2012) bottom shear stress, τ_b, is calculated by,

$$\tau_b = \rho \times g \times R \times S \ (7)$$

Where ρ is density of water [kg/m^3], g is gravity (m^2/s), R is hydraulic radius (m) and S is slope. Critical shear stress for cohesive is calculated by

$$\tau_c = \tau_{cn} \left(1 + \frac{a \times e^{b \times \rho_b}}{d^2} + \frac{c_5}{c_3 \times d} \right) \ (8)$$

Where a are b coefficients specified by Lick (2009) to be 8.5X10^{-16} m^2 and 9.07cm^3/g, ρ_b is bulk density (kg/m^3). The values of c_3 and c_5 can be determined by the following equations:

Table 2 Parameters used to compute the calculated and modeled resuspension rates

	Parameter	Values	Sources
a	coefficient for the effects of particle packing on the critical shear stress $t_c[m^2]$	$8.5x10^{-16}$	Lick (2009)
a_{aSS}	coefficient for the effects of particle packing on the critical shear stress $t_c[m^2]$ attached	-1.6x10-19	Calibrated
a_{aSS2}	coefficient for the effects of particle packing on the critical shear stress $t_c[m^2]$ attached	$8.5x10^{-16}$	Lick (2009)
a_{aS}	coefficient for the effects of particle packing on the critical shear stress $t_c[m^2]$ attached	$8.5x10^{-16}$	Lick (2009)
a_{aS2}	coefficient for the effects of particle packing on the critical shear stress $t_c[m^2]$ attached	$8.5x10^{-16}$	Lick (2009)
a_{aBF}	coefficient for the effects of particle packing on the critical shear stress $t_c[m^2]$ attached	$8.5x10^{-16}$	Lick (2009)
a_{aBF2}	coefficient for the effects of particle packing on the critical shear stress $t_c[m^2]$ attached	-3.6x10	Calibrated
a_u	coefficient for the effects of particle packing on the critical shear stress t_c $[m^2]$ unattached	$8.5x10^{-16}$	Lick (2009)
b	coefficient for the effects of particle packing on the critical shear stress t_c $[m^3/g]$	$9.1x10^{-3}$	Lick (2009)
b_{aSS}	coefficient for the effects of particle packing on the critical shear stress t_c $[m^3/g]$ attached	$2.5x10^{-2}$	Calibrated
b_{aSS2}	coefficient for the effects of particle packing on the critical shear stress t_c $[m^3/g]$ attached	$2.23x10^{-2}$	Calibrated
b_{aS}	coefficient for the effects of particle packing on the critical shear stress t_c $[m^3/g]$ attached	$2.09x10^{-2}$	Calibrated
b_{aS2}	coefficient for the effects of particle packing on the critical shear stress t_c $[m^3/g]$ attached	$2.22x10^{-2}$	Calibrated
b_{aBF}	coefficient for the effects of particle packing on the critical shear stress t_c $[m^3/g]$ attached	$2.30x10^{-2}$	Calibrated
b_{aBF2}	coefficient for the effects of particle packing on the critical shear stress t_c $[m^3/g]$ attached	$1.94x10^{-2}$	Calibrated
b_u	coefficient for the effects of particle packing on the critical shear stress t_c $[m^3/g]$ unattached	$9.1x10^{-3}$	Lick (2009)
c_3	prg(s-1)/6, coefficient for the effect of clay on the critical stress t_c $[N/m^3]$	$1.4x10^3$- $2.7x10^3$	Calculated
c_5	coefficient for the effect of clay on the critical stress t_c $[N/m^2]$	2.08 - $10x10^3$	Calculated
C_a	concentration of *E. coli* attached to sediment in the water column[cfu/100mL]	0 - $3.8x10^6$	Measured
C_{ab}	concentration of *E. coli* attached to sediment in the bed $[cfu/m^2]$	$8.2x10^3$- $1.6x10^8$	Measured
C_u	concentration of *E. coli* attached to sediment in the water column [cfu/100mL]	$3.8x10^4$- $2.9x10^6$	Measured
C_{ub}	concentration of *E. coli* unattached to sediment in the bed $[cfu/m^2]$	$4.4x10^1$- $1.3X10^4$	Measured
d	diameter of sediment particles to which *E. coli* attach [m]	$4.4x10^{-5}$- $6x10^{-4}$	Manufactures Specifications
E_0	coefficient in the predicted resuspension rate of all sediment particles [m/s]	$1x10^{-6}$	Lick (2009)
E_{a0}	coefficient in the predicted resuspension rate of attached particles [m/s]	$1x10^{-6}$	Lick (2009)
E_{u0}	erosion rate at the threshold of erosion of unattached particles [m/s]	$1x10^1$	Calibrated
F_b	binding force as a function of the particle diameter and specific gravity [N]	$8.0x10^{-9}$-$7.5x10^{-7}$	From Figure in Lick (2009)

Table 2 continued			
n	exponent in the predicted resuspension rate [-]	2.00	Lick (2009)
n_{aSS}	exponent in the predicted resuspension rate attached [-]	7.00	Calibrated
n_{aSS2}	exponent in the predicted resuspension rate attached [-]	2.00	Calibrated
n_{aS}	exponent in the predicted resuspension rate attached [-]	2.00	Calibrated
n_{aS2}	exponent in the predicted resuspension rate attached [-]	2.00	Calibrated
n_{aBF}	exponent in the predicted resuspension rate attached [-]	-11.00	Calibrated
n_{aBF2}	exponent in the predicted resuspension rate attached [-]	2.00	Calibrated
n_{uSS}	exponent in the predicted resuspension rate unattached [-]	2.10	Calibrated
n_{uSS2}	exponent in the predicted resuspension rate unattached [-]	2.60	Calibrated
n_{uS}	exponent in the predicted resuspension rate unattached [-]	2.20	Calibrated
n_{uS2}	exponent in the predicted resuspension rate unattached [-]	2.70	Calibrated
n_{uBF}	exponent in the predicted resuspension rate unattached [-]	2.10	Calibrated
n_{uBF2}	exponent in the predicted resuspension rate unattached [-]	1.70	Calibrated
Q	discharge [m^3/s]	$1.6x10^{-3}$-$1.6x10^{-02}$	Measured
R	hydraulic radius [m]	0.1 - 0.35	Measured
R_a	predicted attached resuspension rate [$cfu/m^2/s$]	$3.6x10^{-8}$-$2.8x10^{-5}$	Calculated
R_{ac}	calculated attached resuspension rate [$cfu/m^2/s$]	0-$3.9E^{-5}$	Calculated
R_u	predicted unattached resuspension rate [$cfu/m^2/s$]	$1.2x10^{-8}$- $3.0x10^{-4}$	Calculated
R_{uc}	calculated unattached resuspension rate [$cfu/m^2/s$]	$3.0x10^{-5}$ - 1.7 x 10^{-5}	Calculated
S	slope [-]	0.01	Measured
SA	Surface Area of sediment [m^2]	3.0 & 1.5	Measured
r_b	bulk density of the sediment [kg/m^3]	1280 - 1520	Measured
t_b	bottom shear stress [N/m^2]	10.2 - 13.2	Calculated
t_c	critical shear stress for cohesive sediment [N/m^2]	$0.6x10^4$ - $8.0x10^4$	Calculated
t_{cn}	critical shear stress for non-cohesive sediment [N/m^2]	0.018 - 0.25	Calculated
Where subscripts are SS is sand-silt, SS2 is sand-silt at 23 cm, S is sand, S2 is sand at 23 cm, BF is biofilm, and BF2 is biofilm at 23 cm.			

$$C_3 = \frac{\pi}{6} \times g(\rho_b - \rho) \ (9)$$

$$C_5 = \frac{F_b}{d^2} \ (10)$$

Where, F_b is a binding force as a function of the particle diameter and is specified in Lick (2009) (N), the value in these equations varied for each bottom sediments . Using these equations calculated resuspension rates for *E. coli* in the particle attached and unattached phases were completed. All parameters are shown in Table 2 for each filtted parameter and where it was derived.

Model Sensitivity and Calibration

Prior and after model calibration a sensitivity analysis was conducted to identify the variables most likely to influence the predicted resuspension values and identify model sensitivity. To calculate the relative sensitivity Equation 11 (James and Burges 1982; Jesiek and Wolfe 2005; Parajuli et al. 2009; White and Chaubey 2005) was used

$$S_{Y_i} = \frac{(\mathrm{R}_i - \mathrm{R}_b)\mathrm{Y}_b}{(Y_i - Y_b)R_b} \ (11)$$

Where S_{yi} is the relative sensitivity index , P_i is ith predicted value, P_b is the baseline predicted value, Y_i is the ith model input parameter, and Y_b is the baseline value. The input parameters that were analyzed for relative sensitivity were those specified by Lick as fitting parameters found through calibration of his data (2009): a_a, a_u, b_u, b_a, n_a, n_u, E_{oa} and E_{ou}. To determine the most sensitive parameters for calibration Equation 11 was used. The baseline values, minimum and maximum value, and incremental change associated with each input parameter are shown in Table 3. The relative sensitivity was used to set lower and upper bounds on calibration parameters. Sensitivity index classifications according to Zerihun (1997), are No sensitivity (N) $0 < |S_{yi}| <$

Table 3 Sensitivity Parameters

Y	Yb	Min	Max	Interval
a	$8.5\text{x}10^{-16}$ (m2)	0.0	1.00E^{-15}	1.00E^{-16}
b	$9.1\text{x}10^{-3}$ (m3/g)	0.0	1.00E^{-02}	1.00E^{-03}
n	2.0	0.0	5.0	0.1
E_o	$1\text{x}10^{-6}$(m/s)	1.00E-06	1.0	$1\text{x}10^{-n}$*

***Denotes change increase in n by one for each interval**

0.10, Low sensitivity (L) 0.10 <$|S_{yi}|$< 0.50, Moderate sensitivity (M) 0.50 <$|S_{yi}|$< 2.0, High sensitivity (H) 2.00 < $|S_{yi}|$< 5.00, Very high sensitivity (VH) $|S_{yi}|$> 5.00.

The resuspension equations were modified by calibrating the coefficients specified by Lick. The values of b_a, and n_u were calibrated for the each of the bottom sediments and depths of water. The value of E_{uo}, representing erosion rate, was modified for all unattached experiments uniformly due to the property being the same for all *E. coli* cells. Using the sensitivity analysis as a guide of sensitivity the calibrations were completed using Matlab. The first parameters calibrated were the least sensitivity a_a, a_u, b_u, and E_{uo}. The parameter a, was deemed insensitive, it was not considered in the calibration procedure for resuspension. Parameters used for the sensitivity analysis were calibrated individually to optimize measured and predicted resuspension. The threshold of erosion, E_o, was held constant for all bottom sediments but was set at 1E1 to represent the erosion of single *E. coli* for R_u calculations. When predicting R_a, the b_a parameter was optimized for each sediment type. Parameters n_a and n_u were optimized for each bottom sediments and water depth. Once the calibration was completed the sensitivities for the new parameters were completed. The sensitivities were completed by calculating the sensitivity in Equation 11 for a_a, a_u, b_u, b_a, n_a, n_u, E_{oa} and E_{ou}, by changing the values ±5% and ±20%. This was completed in order to measure the sensitivity of the calibrated parameters in the model.

Results and Discussion

After the experimental procedures were completed, the raw data was organized and checked for quality control. Statistical analysis was completed on the data sets on the effects of flow rate and bottom sediments type on various parameters. The background concentrations of both the bottom sediments and water column were test and compared. Suspended particle sizes and turbidity were analyzed for each experiment. The *E. coli* attachment ratio for both flume segments was computed using a mass balance approach. Resuspension was also calculated using the physical mass balance approach for both attached and unattached *E. coli*; however it was completed only between the first and second sampling locations. Once the resuspension were calculated the model of sediment resuspension was calibrated to model the results in the flume. The calibration of the model

was completed by changing various parameters for each bottom sediments and water depth. After calibration the sensitivity of the calibrated parameters was calculated.

E. coli Concentrations in Bottom Sediments and Water

In order for the experiment to have an accurate mass balance, the background concentrations of water and bottom sediments were measured in the experiments. Correlations and statistical analysis were completed on each bottom sediments with different flows and depths. The bottom sediments concentrations for each experiment were measured to test the effect of sediment concentrations on water column concentrations. The water inlet *E. coli* concentrations were measured prior to entering the flume to measure the recirculation of *E. coli* in the flume. The *E. coli* concentrations were compared to the water column concentrations taken at the two collection locations.

Prior to setting the flow for each experiment, the initial *E. coli* concentrations in the bottom sediments were measured. The initial samples collected before the inoculation was measured in order to understand if the rinsing procedures effectively removed *E. coli* from previous experiments from the system. Another background bottom sediments sample was collected after the inoculation was completed to compare the before and after effects of the inoculation. The average concentrations of the sediment for sand was 2.90E6 (δ=1.59E5) cfu/g, for sand-silt was 5.59E5 (δ=8.74E5) cfu/g, and for biofilm was 6.64E3 (δ=1.84E3) cfu/g (Figure 3), where δ is standard deviation. However, for the bottom sediments two orders of magnitude difference was observed between the sand and sand-silt in comparison to the biofilm bottom sediments. The lower bottom sediments concentrations for biofilm were due to the differences in the *E. coli* inoculation procedures. The

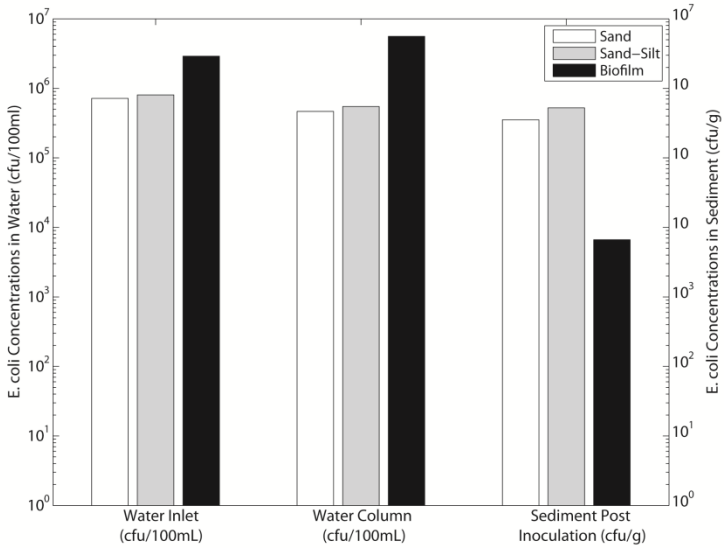

Figure 3 Background concentrations of *E. coli*

E. coli was not mixed into the biofilm layer after inoculation to preserve the biofilm.

After steady state had been reached the inlet *E. coli* concentrations were measured at the same time samples were collected (5, 15, 30, 45, and 60 minutes after the start of the experiment). The *E. coli* concentrations differed between the collection locations as well as the time periods. No statistically significance between locations collected at different time periods was found (P-value < 0.05). This was expected because the experiments were conducted under steady state conditions and were taken as independent points in the experiment for each time period. Because of the statistical independence of the samples, for analysis, values at each point in time were averaged (Table 2). Background *E. coli* concentrations in the water column were collected before the inlet, after the inoculation. For sand the background water concentration was 7.17E5 (δ=4.12E5) cfu/100mL, for sand-silt 4.66E5 (δ=2.49E5) cfu/100mL, and for biofilm 3.53E5 (δ=3.84E5) cfu/100mL (Figure 3).

The concentrations in the water column also differed within the bottom sediments type and inoculation concentrations. For sand the average *E. coli* concentration water column were 8.04E5 (δ=4.47E5) cfu/100mL, for sand-silt 5.47E5 (δ=2.15E5) cfu/100mL, and for biofilm 5.24E5 (δ=4.04E5) cfu/100mL (Figure 3). For the sand and sand-silt experiments correlations were found between flow rate and *E. coli* concentrations in the water column (P-value = 0.0001 and P-value = 0.0002, respectively; Appendix C). The *E. coli* concentrations measured in the water column are above the single sample maximum limit set by the U.S. EPA, 235 cfu/100mL, and are more representative of an urban environment contaminated by combined sewer overflow events caused by large storms (Passerat et al. 2011). There was an impact of *E. coli* concentration on the bottom sediments on the background water column *E. coli* concentrations. As shown in Figure 3 the water column concentrations and water inlet concentrations are within an order of magnitude difference for all bottom sediments.

The background concentrations collected before the weir at the inlet were unusually high for the lowest flow rates in all bottom sediments, in comparison to the water column in the flume. The probable cause of the concentration difference is the flow straightener which

acted as a weir prior to the inlet of the flume. This could have caused some deposition of larger particles and associated *E. coli* creating a zone of higher concentration behind the flow straightener. The weir effect likely removed larger particles and did not affect free floating bacteria, as they would not have been removed by the flow straightener. For this reason resuspension calculations were based on the second flume segment instead of between the inlet and the first collection location.

Suspended Sediment Sizes and Turbidity of Water Column

Turbidity was measured for each water collection point as well as for the composite samples. Statistical analysis found effects of flow and sediment type on turbidity in the water column (Table 5 and Table 6). A statistically significant difference was observed between the turbidity of biofilm compared to the sand and sand-silt (P-value < 0.0001), but not between the turbidity of water samples collected from the sand-silt and sand bottom sediments (P-value = 0.7168, Table 5). This is likely due to the biofilms cohesive nature, which allows sloughing of biofilm causing a much higher turbidity in comparison to the sand and sand-silt. Additionally, the in-line weir was potentially less effective in removing the suspended biofilm particles than the sand and sand-silt particles, and therefore, more particles were recirculated through the system.

There was also significant correlation of flow rate and turbidity for the biofilm experiments (P-value = 0.0001, Appendix C). Biofilm was observed to slough off easier than the sand and sand-silt particles increasing the turbidity of the water. The different flow rates for each bottom sediments had a statistically significant impact on turbidity in the water column (P-value <0.001). Differences were observed between the high flow and both the medium and low flows; however, there was not a statistically significant difference between the medium

Table 4 Particle Size and Turbidity Statistics

Bottom sediments	Average Particle size (µm)	Average Turbidity (NTU)
Biofilm	20.4 a	26.5a
Sand-Silt	10.7ab	2.7b
Sand	8.6 b	3.6b
Flow Rates		
High	13.0a	17.5a
Medium	12.0a	8.2b
Low	14.7a	7.2b

Values followed by different letters indicate statistical difference according to Tukey's pairwise comparison at α= 0.05

and low flows on turbidity (P-value = 0.5632). Results of particle size and turbidity comparisons are listed in Table 4. The results suggest there was not enough of a difference between the low and medium flow rates that were selected below the critical shear stress to result in significantly different turbidity concentrations in the water column.

The interactions of depth on the turbidity were also investigated. The statistical analysis found effects of depth and bottom sediments type on turbidity to be statistically significant (P-value <0.0001 and P-value <0.0001, respectively; Table 5) and interactions between the two were also statistically significant (P-value <0.0001). Different bottom sediments contained various particles sizes and caused variations in critical shear stresses. The changes in critical shear stress would create distinct turbidities within each bottom sediment. For sand-silt and biofilm bottom sediments (but not sand) there was a significant correlation between the depth and the observed turbidity. This could be caused by the change in shear stress observed due to the increase of hydraulic radius. As shown in Equation 7, bed shear stress is dependent on the hydraulic radius of the scenario.

Measurements of turbidity were supplemented with analysis of particles sizes taken at the second sampling location. Statistical analysis found a statistically significant effect on particle sizes (P-value < 0.001) from the different bottom sediments (Table 5), with the biofilm having significantly higher average particle sizes in the water column than the sand-silt and sand bottom sediments. No statistically significant effect was observed between flow rate and average particle sizes. This could be because particles were removed by the weir and therefore average particle sizes were affected more by bottom sediments type. The average size of particles for the bottom sediments were sand 600 µm, silt 44 µm diameter, and biofilm 322 µm. In comparison the average particle sizes in the water column were sand 8.6 µm, silt 10.7 µm diameters, and biofilm 20.4 µm. The sand had the smallest particles sizes suspended this is probably caused by the bottom sediments having the lowest concentration of small particles to resuspended. The sand-silt bottom sediments had more small particles to resuspend and therefore had a higher size for the average particle size in the water column. The biofilm had a completely different size range do to the EPS holding particles together causing a much higher particle size to appear. However these particles had a lower bulk density due to the organic material.

The statistical analysis determined that the mean particle sizes in the water column were not impacted by water depth (Table 6). Although there was a change in the hydraulic radius which affects the bottom shear stress, it was not a significant change to impact the particle sizes measured. Statistical analysis found an impact of bottom sediments on particle sizes, which confirms the findings in the single depth experiments, which had similar turbidities.

Statistical analysis also found impacts of attached *E. coli* concentration on turbidity. Attached *E. coli* concentrations had a significant correlation with turbidity in biofilm (P-value = 0.014). While the sand and sand-silt bottom sediments did not have a significant correlation. Other researchers have found *E. coli* is correlated to turbidity during resuspension experiments conducted in estuaries and streams (Fries et al. 2008; Muirhead et al. 2004). McDaniel's (2011) experiments were completed in a recirculating flume setting with varying flows and measured resuspension using initial deposition of fecal matter from bovine species on a rock bed. The experiments found significant correlation between attached *E. coli* concentration and turbidity. However, studies have found weak correlation between fecal coliforms and turbidity (Cho et al. 2010; Dorner et al. 2007; Henson et al. 2007).

Fraction of Attached and Unattached *E. coli*

The bottom sediments were inoculated to increase the amount of *E. coli* available for resuspension, and to better provide insight into the process. The *E. coli* added to the bottom sediments was freely suspended cells, and *E. coli* which was measured as attached in the water column was caused by interactions with particles during the inoculation procedure. Attachment ratios in each of the three bottom sediments are shown in Figure 4 A-C for each flow rate and depth. The attachment ratios were measured for five time intervals for each flow rate. As seen in the Figure 4, the attachment ratios increased as flow increased which matches the original principle of increased shear stress causing an increase in resuspension of particles and bacterial attachment in the water column. Other studies have found correlations between sediment transport and increasing shear stress (Krishnappan 2007; Lick et al. 1995; Stone et al. 2008; Witt and Westrich 2003). Resuspension models have also been had equations based on the sediment shear stress (Collins and Rutherford 2004). However,

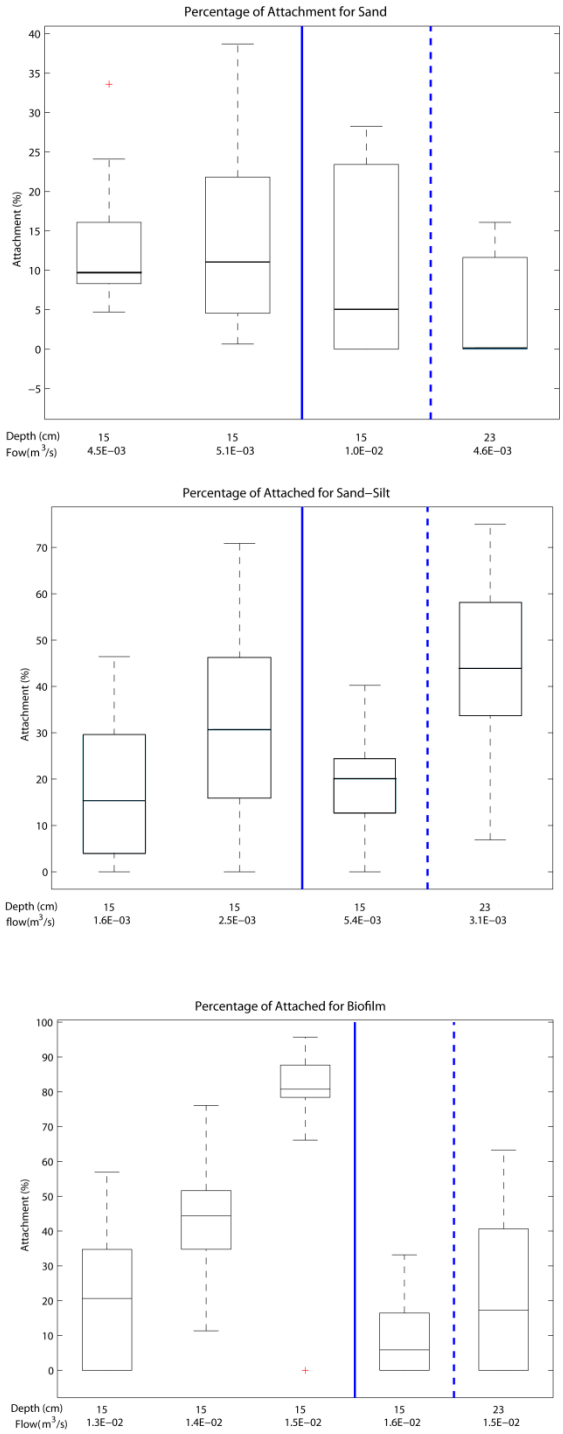

Figure 4 Attachment percentages at varying flow rates and water depths for A) Sand, B) Sand-Silt, and C) Biofilm bottom sedimentss. The critical shear stress is identified by the solid vertical line. The values at 23 cm water depth are separated by a dashed line for comparison to similar flow rates.

the decrease after the critical shear stress point was exceeded was not in originally theorized. The decrease of attachment could be caused by the superficially attached *E. coli* to be removed due to the high shear stress. There could also be particle interaction due to higher resuspension of particles, which allow physically remove *E. coli*.

Statistical analysis found impacts on percent of *E. coli* attached to particles, due to bottom sediments type, flow rate, and interactions between bottom sediments and flow (Table 5). Due to the effects of cohesive and noncohesive shear stress the percent of *E. coli* attached to particles was expected to change with the bottom sediments; the statistical analysis found some statistically significant differences among the three bottom sediments. The analysis found statistically significant differences of attachment of *E. coli* between sand and biofilm bottom sediments. There are the two extremes in the bottom sediments, caused by the organic matter and size particles; therefore a difference of attachment was expected with the bottom sediments. Analysis was also completed on only two experiment runs for similar flow rates and differ depths of water (Table 6) this set only contained two experimental runs in

comparison to Table 5 which contained all the flow rates and only one depth. Statistical analysis also found an impact of depth and bottom sediments on the attachment ratios (P-value <0.040, P-value <0.001 respectively). The pairwise comparison found a difference between the biofilm and sand-silt attachments. This is unexpected due to the biofilm and sand-silt having similar initial particle sizes. However, the biofilm has a significant cohesive factor which could have an effect on the attachment ratios.

As the bottom sediments diameter decreases the cohesiveness increases (Lick et al. 1995; van Rijn 2007) and biofilm has added cohesiveness due to the presence of EPS (Droppo et al. 2007; Krishnappan 2007; Paterson 1989). The highest *E. coli* attachment to particles was found in the water samples collected during the biofilm bottom sediments experiments. The average *E. coli* attachment for the experiments conducted at 15 cm water depth and biofilm bottom sediments was 37% (δ=30%). The theory of biofilm having the greatest attachment of the three bottom sediments, caused by the high cohesive strength of EPS, was proven. Krishnappan found the more sites in sediment occupied with microbial growth created lower erosion rates by increasing the cohesion (Krishnappan 2007). Paterson found a direct correlation between increased shear stress and the number of diatoms in the sediment (Paterson 1989). Droppo in a flume setting was able to grow biofilm and show gradual increase of the erosion rate with increased growth (Droppo et al. 2007). The average *E. coli* attachment percentage for the experiments conducted at 15 cm water depth, sand-silt bottom sediments was 23% (δ=19 %), and sand bottom sediments was 12% (δ=11%). The *E. coli* attachment in water samples collected during the sand bottom sediments experiments was lower than the *E. coli* attachment in water samples collected during the sand-silt bottom sediments. This is due to the increased cohesive strength of the sand-silt mixture in comparison to an all sand mixture (Lick et al. 1995; Redondo et al. 2001; van Rijn 2007). Sand attachment was expectedly much lower than the biofilm due to its low organic fraction (entirely silica). The sand and silt used for the experiment were ground from quarts classification to appropriate sizes. However, the biofilm bottom sediments were inoculated with organic materials in the form of the stream biofilm. The increased organic materials allowed more cohesion than in the sand and sand-silt bottom sediments.

When the percent *E. coli* attached was compared between the experiments conducted at 15 cm depth and 23 cm depth, the sand decreased by 69% and biofilm

decreased by 66% whereas the sand-silt *E. coli* percent attachment increased by 34%. The decrease in attachment supports the initial theory that bottom shear stress increases with the increase of flow and causes higher resuspension. Therefore when the depth changes and flow rate stays the same, shear stress increases due to the extended hydraulic radius of the flume. The intensified critical shear stress is crossed and attachment decreased for sand and biofilm at the 23 cm depth. The sand-silt increase in *E. coli* attachment was unexpected, as the intensified critical shear stress was expected to be crossed.

Attachment ratios found are comparable to attachment amounts observed in the field. Passerat found an attachment of 77% to suspended matter or solids during a combined sewer overflow event (Passerat et al. 2011), and the magnitude of attachment was high during wet weather conditions than in dry weather conditions. Krometis (2007) found 40% attachment with fecal coliforms, *E. coli* and entercocci. Krometis looked at different storm events to explain the partitioning of attachment in different microorganisms and pathogens.

Table 5 Two Way ANOVA for Flow Rate and Sediment Comparisons

	Mean Particle Size	Turbidity	Attachment	Total Resuspension	Attached Resuspension	Unattached Resuspension
Flow Rate Comparison	P-Value	P-Value	P-Value	P-Value	P-Value	P-Value
Overall ANOVA	**0.0056**	**0.0010**	**0.0001**	**0.0001**	**0.0001**	**0.0140**
Flow	0.8945	**0.0010**	**0.0001**	**0.0001**	**0.0004**	0.0563
Bottom sediments	**0.0064**	**0.0010**	**0.0010**	**0.0009**	**0.0158**	0.0976
Flow×Bottom sediments	**0.0171**	**0.0010**	**0.0003**	**0.0032**	**0.0004**	**0.0340**
Pairwise Comparison Parameters						
High-Low Flow	0.9183	**0.0010**	0.5875	**0.0001**	**0.0003**	0.1046
High-Medium Flow	0.9714	**0.0010**	**0.0001**	**0.0015**	0.0696	0.0763
Low-Medium	0.7983	0.5632	**0.0008**	0.3365	0.0744	0.9981
BF-SS	0.0647	**0.0010**	0.2992	0.7684	0.3993	0.9847
BF-Sand	**0.0196**	**0.0010**	**0.0006**	**0.0010**	**0.0115**	0.1528
SS-Sand	0.8926	0.7168	0.0666	**0.0102**	0.2361	0.1312
High-BF - High-SS	0.8979	**0.0001**	0.9514	0.5868	0.1035	1.0000
High-BF - High-Sand	0.9996	**0.0001**	1.0000	0.0721	0.9997	**0.0298**
High-SS - High-Sand	0.9969	0.9997	0.9513	**0.0003**	0.3166	**0.0303**
Medium-BF - Medium-SS	0.3192	**0.0001**	**0.0093**	0.9874	0.8765	1.0000
Medium-BF - Medium-Sand	0.1897	**0.0001**	**0.0001**	0.9839	0.7833	1.0000
Medium-SS - Medium-Sand	1.0000	1.0000	0.4242	1.0000	1.0000	1.0000
Low-BF - Low-SS	0.0585	**0.0001**	1.0000	0.3856	**0.0099**	1.0000
Low-BF - Low-Sand	0.1068	**0.0001**	0.9880	0.2652	**0.0042**	1.0000
Low-SS - Low-Sand	1.0000	0.7992	0.9999	1.0000	1.0000	1.0000
High-BF - Medium-BF	0.3630	**0.0001**	**0.0001**	0.2177	**0.0113**	1.0000
High-BF - Low-BF	0.1042	**0.0001**	0.8769	**0.0060**	**0.0001**	1.0000
Low-BF - Medium-BF	0.9788	0.8719	**0.0001**	0.4943	**0.0265**	1.0000
High-SS - Low-SS	0.7915	0.9943	1.0000	1.0000	0.9999	1.0000
High-SS - Medium-SS	0.8716	1.0000	0.8538	0.9998	0.9928	1.0000
Low-SS - Medium-SS	1.0000	0.9943	0.7357	1.0000	1.0000	1.0000
High-Sand - Medium-Sand	0.9924	0.9930	0.9998	**0.0016**	0.9123	1.0000

Table 5 continued						
High-Sand - Low-Sand	0.9996	0.9240	0.9999	**0.0009**	0.7915	1.0000

For this table SS denotes sand-silt bottom sediments, BF denotes for biofilm bottom sediments. The High denotes the highest flow, Medium denotes medium flow, and Low denotes the low flow for all bottom sediments.

Table 6 Two way ANOVA for Depth and Bottom sediments comparison

	Mean Particle Size	Turbidity	Attachment	Total Resuspension	Attached Resuspension	Unattached Resuspension
Depth Comparison	P-Value	P-Value	P-Value	P-Value	P-Value	P-Value
Overall ANOVA	**0.0400**	**0.0001**	**0.0001**	0.1609	0.5990	0.26
Depth	0.3330	**0.0001**	**0.0037**	**0.0465**	0.2066	0.20
Bottom sediments	**0.0348**	**0.0001**	**0.0001**	0.7737	0.5754	0.33
Depth × Bottom sediments	0.1147	**0.0001**	**0.0001**	0.1684	0.6432	0.26
Pairwise Comparison Parameters						
BF-SS	**0.0267**	**0.0001**	0.2203	0.9515	0.5453	0.50
BF-Sand	0.3068	**0.0001**	**0.0001**	0.9092	0.8620	0.34
SS-Sand	0.4669	**0.0001**	**0.0002**	0.7559	0.8511	0.95
15 BF - 15 SS	0.1032	**0.0001**	**0.0005**	0.8313	0.8696	1.00
15 BF -15 Sand	0.1279	**0.0001**	**0.0001**	0.8995	0.9004	1.00
15 SS - 15 Sand	1.0000	0.3203	0.3656	1.0000	1.0000	1.00
23 BF - 23 SS	0.8683	**0.0001**	0.2839	0.9688	0.9987	0.48
23 BF -23 Sand	0.9975	**0.0001**	0.3766	0.5884	0.9996	0.32
23 SS - 23 Sand	0.6158	**0.0001**	**0.0019**	0.9542	0.9816	1.00
15 BF - 23 BF	0.3170	**0.0001**	**0.0001**	0.0992	0.7039	0.30
15 SS - 23 SS	0.9937	**0.0001**	0.8476	0.9680	0.9790	1.00
15 Sand - 23 Sand	0.9368	**0.0460**	0.9327	1.0000	1.0000	1.00

For this table SS denotes sand-silt bottom sediments, BF denotes for biofilm bottom sediments. The 15 denotes the 15 cm depth of the water column, and 23 denotes the 23 cm depth of water column.

Despite the changes in pathogen loading rate there was an increase of attachment and concentration during the first phase of the storm, similarly to the flume results, where the increase in flow rate increases the attachment, sand increased from 10% to 12%, sand-silt increased from 13% to 32% and biofilm increased from 21% to 81%. Characklis (2005) also looked at attachment fractions and found 20-35% of the *E. coli* tested was associated with particles during normal flow and up to 30-55% were attached to particles during a storm event. Results of the average fraction of *E. coli* attachment in the sand-silt and biofilm, 23% and 37% respectively, were comparable, although none of the compared values from Characklis, Passerat, or Krometis, were derived under flume conditions. The *E. coli* attachment to particles during the experiments conducted under the sand bottom sediments had lower *E. coli* attachment fraction was 12%; this outcome was lower than previous experiments, likely due to the lack of organic or cohesive matter (Hipsey et al. 2006; Karunakaran et al. 2011)

Resuspension of Attached and Unattached *E. coli*

Resuspension values were calculated between the two sampling locations and for attached and unattached *E. coli* using Equations 3 and 4. Figure 5 shows the attached and unattached resuspension rates for the second segment (Figure 1). Negative resuspension implies deposition was occurring between the two sampling locations. Statistical analysis found flows and bottom sediments had impacts on total *E. coli* resuspension, attached *E. coli* resuspension, and unattached *E. coli* resuspension (Table 5). As shown in the Figure 5 the resuspension rate increased for attached and unattached *E. coli* after the critical shear stress was surpassed for both sand and biofilm bottom sediments. However, for the sand-silt bottom sediments, the unattached *E. coli* resuspension rate increased whereas the attached *E. coli* resuspension rate decreased. The attached *E. coli* resuspension rate *E. coli* was lowest in the experiments conducted on the silt-sand bottom sediments. Sand-silt experiments also had the only attached *E. coli* resuspension rate where deposition was observed after the critical shear stress was surpassed. Deposition could have been caused by particle interactions between the bacteria, sand and silt. More cohesion would be expected in the sand-silt than in just the sand. However, due to higher density particles than in biofilm, the sand-silt fraction could have resuspended in the first segment and settled in the second segment.

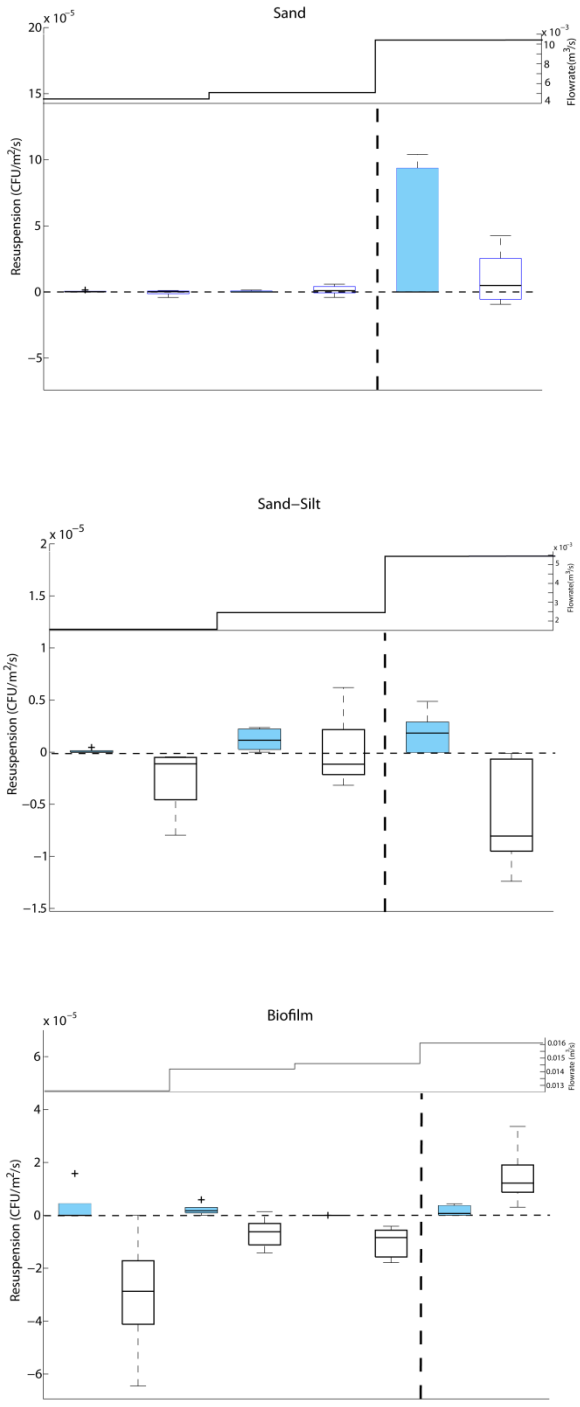

Figure 5 *E. coli* resuspension calculated at position 2 in the attached (unfilled) and unattached (filled) phases for A) sand, B) sand-silt, and C) biofilm bottom sedimentss. The vertical dashed line shows the flow where the critical shear stress is exceeded. Positive values represent resuspension and negative values represent deposition.

In comparison to other studies the measured and predicted resuspension rates were rather low. Jamieson (2005) calculated 8200-15,000 cfu/m^2/s whereas the highest resuspension value calculated was 1.09E-4 cfu/m^2/s. Pandey (2012) also measured higher resuspension rates ranging between 11-167 cfu/m^2/s. The *E. coli* sediment concentrations can also be compared to Jamison's study which ranged from 1.2E5 to 5.5E5 cfu/100mL; whereas in the concentrations of this study averaged 3.52E07 (δ=6.29E07) cfu/100mL for this study. The discrepancy in resuspension rates could be caused by flow rates and therefore different shear stress. Both Jamieson's and Pandey's studies were completed in the field and enumerated effects of resuspension. Jamieson created artificial flows after seeding the sediment bed with NAR *E. coli*, whereas Pandey measured *E. coli* concentrations under various natural flow conditions Jamieson was using a stream measured flow rates from zero to 8.0E-2 m^3/s and Pandey had an average flow rate of 3.6 m^3/s. A maximum flow rate of 1.61E-2 m^3/s, was measured for the flume, which could possibly explain the low resuspension rates relative to the calculated rates observed in the field.

In Figure 5 shows less unattached

resuspension than expected; more unattached resuspension was expected due to the relatively small size of *E. coli*. This could be caused by the separation method used to differentiate the *E. coli* in the water column. A more intensive method to estimate the total amounts of attached and unattached *E. coli* could have been used such as centrifugation in addition to filtration and settling (Liu et al. 2011; Soupir et al. 2008). Due to the small size and buoyancy of a single *E. coli* cell, no deposition should have occurred (Baldwin et al. 1995; Pachepsky et al. 2006). Equations (4-5) use a mass balance to determine attached and unattached resuspension rates. However, if there was little to no difference in concentration between the two locations it could have caused deposition and resuspension to be equal. All of the resuspension might have occurred after inoculation had been completed and the pumps were turned back on before the initial sampling at time zero. The background concentration of *E. coli* in the water column could have remained high due to the lack of deposition of unattached *E. coli* in the recirculating water. The amount of unattached resuspension could also be dampened due to the high concentrations of *E. coli* in the water column, making it difficult to differentiate the background concentration from the flux of resuspending *E. coli*. These factors could help explain the low calculated unattached *E. coli* resuspension. Due to the low attached resuspension measurements the theory of higher unattached *E. coli* resuspension occurring at higher rates than attached *E. coli*.

Statistical analysis found flows and bottom sediments impact the total *E. coli* resuspension, attached *E. coli* resuspension, and unattached *E. coli* resuspension. The results support the initial postulation that flow and bottom sediments would both impact *E. coli* resuspension. Table 5 lists the statistical results for the flow rate and sediment comparison while Table 6 details the effects of bottom sediments and depth on resuspension values. Although bottom sediments and flow rate have an effect on unattached *E. coli* resuspension (P-value <0.0140), however flow and bottom sediments separately do not (P-value <0.0563, P-value <0.0976 respectively). This difference supports the theory that the unattached *E. coli* resuspension is very low due to the lack of changes in deposition or resuspension. The pairwise comparison for high and low flow rates have significant impacts on total *E. coli* resuspension (P-value <0.001). High and medium flow also had a significant effect on total *E. coli* resuspension (P-value <0.015). There was an impact of flow on attached *E. coli* resuspension for all biofilm experiments. The difference was caused by distinct flow rate

differences in each run, 1.26E-2 m^3/s for the low run, 1.46 E-2 m^3/s for the medium run and 1.61E-2 m^3/s for the high run. When comparing the depth differences with similar flow rates statistical analysis found no effect of depth and bottom sediments on impact the total *E. coli* resuspension, attached *E. coli* resuspension, and unattached *E. coli* resuspension. The results of the depth comparison did not support the initial theory of a significant effect of depth on *E. coli* resuspension. However, there was a significant effect on resuspension total, P-value <0.046 by depth.

Model Evaluation

Modeling resuspension is critical to predict accurately predict water quality. Recently, new models have been developed to predict the resuspension process (Hipsey et al. 2008; Jamieson et al. 2005; Pandey et al. 2012); however, none have been able to test these approaches on data collected from different bottom sediments and controlled flows around the critical shear stress. The experiments provide a valuable dataset due to the controlled parameters including type of sediment, particle diameter, background *E. coli* concentrations, sediment *E. coli* concentrations, flow rate, slope, hydraulic radius, and other variables. Measured values were used to test a model of *E. coli* resuspension first proposed by Pandey et al. (2012), which were a modification of sediment erosion equations.

To calibrate the model, the values of $E_{ou,}$ b_a, and n_u were changed for the resuspension equations 5 & 8 originally by Lick (2009) and are shown in Table 2. Only sampling events in which resuspension occurred were fit to the model; the equations were not used to predict deposition. The three parameters impacting attached *E. coli* resuspension are n_a, a_a, and b_a. For the a_a and n_a values, representing coefficient for the effects of particle packing on the critical shear stress and exponent in the predicted resuspension rate attached respectively. The original values for a_a and n_a are $8.5x10^{-16}$ and 2 respectively. The b_a values, representing coefficient for the effects of particle packing on the critical shear stress, were changed individually for each bottom sediment and are listed in Table 7. The original value of b_a was $9.1x10^{-3}$.

The two calibrated parameters for the unattached *E. coli* resuspension were $E_{ou,}$ and n_u. No adjustment from the values proposed by Lick was required for a_u or b_u, representing

coefficient for the effects of particle packing on the critical shear stress and coefficient for the effects of particle packing on the critical shear stress respectively. The values of a_u and b_u were $8.5x10^{-16}$ and $9.1x10^{-3}$ respectively. The values of n_u, representing exponent in the predicted resuspension rate unattached, were calibrated for each bottom sediments and depth. The original Lick values for n_u were 2. The value of E_{ou}, representing erosion rate at the threshold of erosion of unattached particles, was changed for all of the unattached calculations uniformly across all bottom sediments and depths. The original value of E_{ou} for the model was $1x10^{-6}$. The differences in unattached resuspension were more significant due to magnitude of differences in particle properties between sediments and bacteria.

Figure 6a and 6b show the uncalibrated model's prediction of resuspension compared with the calculated resuspension values measured in the flume. The calculated average unattached *E. coli* resuspension rates were 1.32E-6 cfu/m^2/s for sand, 1.03E-6 cfu/m^2/s for sand-silt, and 1.78E-6 cfu/m^2/s for biofilm. The calculated average attached *E. coli* resuspension rates were 3.84E-6 cfu/m^2/s for sand, -2.84E-6 cfu/m^2/s for sand-silt, and -8.06E-6 cfu/m^2/s for biofilm. The attached *E. coli* resuspension for the biofilm and the sand-silt were negative which indicates that deposition is taking place. This likely occurred because of the initial resuspension from the first segment of the flume and deposited in the second segment. The uncalibrated predicted unattached resuspension rates were 51.0E-12 cfu/m^2/s for sand, 3.30E-12 cfu/m^2/s for sand-silt, and 2.98E-12 cfu/m^2/s for biofilm. The uncalibrated predicted average attached *E. coli* resuspension rates were 5.57E+4 cfu/m^2/s for sand, 5.57E+4 cfu/m^2/s for sand-silt, and .00581E+4 cfu/m^2/s for biofilm. The uncalibrated model under predicted the attached *E. coli* resuspension rates. This is due to the small size of the *E. coli* and cohesion of sediment particles. The uncalibrated model predicted higher unattached *E. coli* resuspension for sand than for the sand-silt and biofilm bottom sediments. For the Lick sediment resuspension model, as the particle size decreases the cohesive shear stress increases and therefore the particle resuspension decreases. Therefore, the model performed as expected for the various bottom sediments, but poorly predicted bacterial processes.

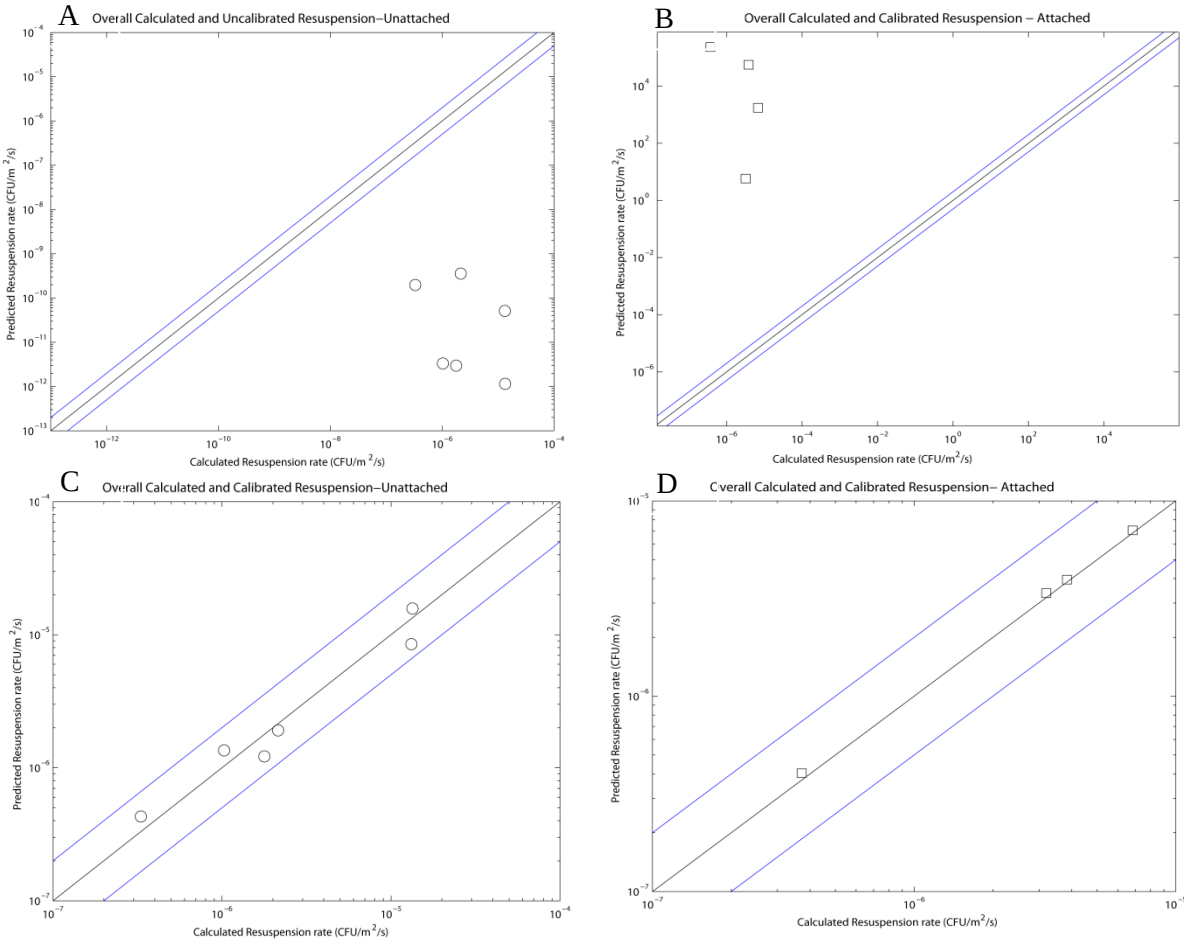

Figure 6 *E. coli* resuspension calculated compared with model output. Solid line indicates perfect agreement and faint lines indicate differences by a factor of 2 A) calculated resuspension & model calibrated unattached, B) calculated resuspension & model calibrated attached C) calculated resuspension & model after calibration unattached d) calculated resuspension & model after calibration attached

The model found an overestimate of attached *E. coli* resuspension in Figure 6a, statistical analysis of the regression found an r^2 value of 0.094. While in Figure 6b an underestimate of unattached *E. coli* resuspension, statistical analysis of the regression found an r^2 value of 0.012. Neither of the comparisons provided a good regression line. The overestimate could be caused by differences in sediment transport equations calibration and flume sediments. One of the possible issues the C5 value was lower than found by Lick (2009), due to the difference in particle diameters. The C5 value calculated by Lick was 21 in comparison the calculated values of C5 ranged from 2.08-4.13. Another might be the different bulk densities of the sediment, and calculated bed shear stresses. For Lick the shear stresses ranged from 0-0.8 N/m^2 in comparison to non-cohesive particles were 0.02-0.25

N/m^2, and the bulk density used by Lick was 1.85 g/cm^3, whereas 1.28-1.52 g/cm^3 was used for the model. Differences in the unattached resuspension calculations could have been caused by major changes of particle diameter and bulk density, especially for unattached *E. coli* cells.

Figure 6 C and D show the predicted *E. coli* resuspension values after calibration compared to the calculated *E. coli* resuspension values. The calibrated model *E. coli* resuspension values for unattached were sand 1.32E-6 $cfu/m^2/s$, sand-silt 1.87E-6 $cfu/m^2/s$, and biofilm 1.21E-6 $cfu/m^2/s$. The calibrated model *E. coli* resuspension values for attached were sand 3.95 E-6 $cfu/m^2/s$, sand-silt -2.17E-6 $cfu/m^2/s$, and biofilm -5.67E-6 $cfu/m^2/s$. The statistical analysis of the regression found an r^2 value of 0.85 for the unattached *E. coli* resuspension model in comparison to the calculated *E. coli* resuspension values. The statistical analysis of the regression found an r^2 value of 0.91 for the unattached *E. coli* resuspension model in comparison to the calculated *E. coli* resuspension values. The calibrated model for the unattached model gives a lower regression due to the size particle difference; however with calibration of the parameters it is possible to model resuspension of unattached *E. coli*. The calibrated values give a wide spread of resuspension values and are better calibrated then the original model output. The calibration performed the best for sand-silt and biofilm than for sand. This is related to environmental factors in the original model calibration in the original model are better represented by sand-silt and biofilm bottom sediments.

Sensitivity Analysis

Once calibration was completed a sensitivity analysis was conducted for each calibration parameter and is detailed in Table 7. The changes made to a_a, and b were categorized as no sensitivity as they were all below 0.10. For the unattached resuspension major changes were made in the erosion threshold, which made a moderate impact due to all the sensitivity indexes being around 1. As shown in Table 7 the highest sensitivity being was found due to the change of n_a and n_u. The n_a was considered to have very high sensitivity and was higher at the 5% change from the base than the 20% change. This is due to the relative difference caused by such close values of n_a. A similar pattern for the sensitivities of n_a were found. However these sensitivities are much higher due to the change in the

original value of 2 proposed by Lick's sediment model. The very high sensitivities are expected considering the modification of the model to such a small organism such as *E. coli*. There was also high sensitivity to the erosion factors for both sediment and unattached *E. coli*. The higher sensitivity rate for unattached is due to the differences caused by much smaller unattached particles.

Table 7 Sensitivity Analysis and Indexes

Baseline Values		**% change from Base**				
		-20	-5	0	5	20
a_a and a_u* = 8.50E-16	S index	0.002307	0.006275	--	0.00758	0.003511
	S index Class	N	N	--	N	N
b_{aSS2} = 2.23E-02	S index	0.005954	0.023815	--	0.023815	0.005954
	S index Class	N	N	--	N	N
b_{aSand} = 2.09E-02	S index	0.005954	0.023815	--	0.023815	0.005954
	S index Class	N	N	--	N	N
b_{aSand2} = 2.22E-02	S index	0.005954	0.023815	--	0.023815	0.005954
	S index Class	N	N	--	N	N
$b_{aBF\ 2}$ = 1.94E-02	S index	0.005954	0.023815	--	0.023815	0.005954
	S index Class	N	N	--	N	N
n_a*= 2	S index	3.4522	5.1523	--	7.0046	11.9142
	S index Class	H	VH	--	VH	VH
n_{uSS} = 2.1E0	S index	99.98	17.84	--	8.167	3.81
	S index Class	VH	VH		VH	H
n_{uSS2} = 2.6E0	S index	2.5103	19.6675	--	19.9655	4.9997
	S index Class	H	VH	--	VH	H
n_{uSand} = 2.2E0	S index	35.5066	10.8727	--	18.6587	4.9839
	S index Class	VH	VH	--	VH	H
n_{uSand2} = 2.7E0	S index	3.7724	19.8588	--	19.9868	4.9999
	S index Class	H	VH	--	VH	H
n_{uBF} = 2.1	S index	99.98	17.84	--	8.167	3.81
	S index Class	VH	VH		VH	H
n_{uBF2} = 1.7	S index	1326.90	554.8647	--	110.29	1.4855
	S index Class	VH	VH	--	VH	M
E_{oa}*= 1.00E-06	S index	1.0026	1.0121	--	0.98661	0.99617
	S index Class	M	M	--	M	M
E_{ou}*= 1.00E+00	S index	3997444	18987861	--	20986586	5996168
	S index Class	VH	VH	--	VH	VH

Sensitivity index classifications according to Zerihun (1997), are No sensitivity N 0 < |Syi|< 0.10, Low sensitivity L 0.10 <|Syi|< 0.50, Moderate sensitivity M 0.50 <|Syi|< 2.0, High sensitivity H 2.00 < |Syi|< 5.00, Very high sensitivity VH |Syi|> 5.00.

*** For all bottom sediments**

Chapter 4 Conclusion

The flume resuspension experiments provided new information about the interactions between *E. coli*, water column and sediments. The experiments were completed under various flow rates for three bottom sediments. There was also a duplicate run completed on similar flow rates with different water depths in order to test the effect of water depth on *E. coli* attachment and resuspension. Unattached and attached resuspension under controlled conditions were analyzed. The experimental control achieved in the flume allowed us great insight into the impacts of the flow and parameters of the sediments on *E. coli* resuspension. Critical shear stresses for the various bottom sediments were calculated based on average particle diameter. Boundaries for mass balances were established in the flume, which allowed us to study attachment and resuspension in close proximity. For resuspension a mass balances was completed to determine the attached and unattached *E. coli* resuspension rates. Statistical analysis was completed, using SAS, for the experiments to measure the impacts of flow and bottom sediments on various parameters.

The results found the attachment ratios increased with increased cohesion and a decrease in particle sizes. Statistical analysis found bottom sediments and flow rates have an impact on attachment percentages. The average percent *E. coli* attached for the different bottom sediments were 37% for biofilm, 23% for sand-silt, and 12% for sand. These results support the increased cohesion of smaller particles and higher EPS encouraged higher percentages of attachment. The percent of attached *E. coli* decreased after the critical shear stress was surpassed; sand attachment decreased by 66%, sand-silt increased by 34%, and biofilm decreased by 69% over the two sample collection locations.

Statistical analysis found flows and bottom sediments impact the total *E. coli* resuspension, attached *E. coli* resuspension, and unattached *E. coli* resuspension. The resuspension rate increased for attached and unattached *E. coli* after the critical shear stress was surpassed for both sand and biofilm bottom sediments. However for sand-silt there was deposition, which could have been caused by resuspension occurring in the first segment of the flume and deposited during the second segment. The calculated unattached *E. coli* resuspension rates were 1.32E-6 cfu/m^2/s for sand, 1.03E-6 cfu/m^2/s for sand-silt, and

1.78E-6 cfu/m^2/s for biofilm. The calculated attached *E. coli* resuspension rates were 3.84E-6 cfu/m^2/s for sand, -2.84E-6 cfu/m^2/s for sand-silt, and -8.06E-6 cfu/m^2/s for biofilm, where negative values indicate deposition. For the calculated attachment ratios there was deposition for both biofilm and sand-silt in the attached *E. coli* phase. In comparison to other studies the measured and predicted resuspension were lower than reported values. The discrepancy for the numbers could be caused by the lower flow rate used in comparison to values obtained from the field.

Using the values of calculated resuspension the model for sediment transport was calibrated to predict *E. coli* resuspension. Using the sediment erosion model (Lick 2009) as a blueprint for attached *E. coli* movement the model was calibrated to model unattached *E. coli*. The statistical analysis of the model comparison found regression values of r^2 value of 0.81 for the unattached *E. coli* resuspension model in comparison to the calculated *E. coli* resuspension values. An r^2 value of 0.91 was found for the attached *E. coli* resuspension model in comparison to the calculated *E. coli* resuspension values. The sensitivity of the equations for the changed parameters, n_a, n_u, E_{ou}, a_a and b_a was completed. Low sensitivity indexes were found for b_a, b_u, a_a and a_u and higher sensitivity for n_u, n_a, E_{oa} and E_{ou} value. Changes to the equations not being made for extremely small particles, such as *E. coli*, would expect high sensitivity.

Implications

The implications of this work are for us to fill the knowledge gap of modeling unattached and attached concentrations of *E. coli*. Jamieson (2004) and Pachepsky (2011), have called for a major improvement of resuspension to be studied to improve knowledge on the effects of *E. coli* transport in water bodies. Work presented in this thesis increases understanding of resuspension of *E. coli* on which further understanding of the mechanics of attachment and resuspension can be built. This initial study will allow others to compare and to look at different variables to investigate resuspension. The modification of equations to model resuspension shows how different particle sizes can effect resuspension. As more sophisticated testing technology is developed it is important that other pathogens or tracer

bacteria can be used to identify fecal contamination and we can model the transportation of bacteria in streams. This study is a platform on which to translate other pathogen species to model and understand the movement of bacteria in streams.

Future Research

The results of this study should be used in the future to assist the understanding of sediment and pathogen transport within stream environments. Improving understanding of transport is critical to predict water quality with models. The equations developed should be used to compare resuspension measured in field experiments. These field studies should focus on evaluating the impacts not studied in the flume such as unsteady flows and how storm hydrographs affect resuspension. There will be a difference in the flows, cohesion and environmental parameters which cannot be imitated in a flume setting. Additional flume studies could be completed to supplement the material presented by considering a wider variation of bottom sediments and flow rates. Once the parameters are investigated and similarly correlated to streams under varying conditions the equations should be included in future models to quantify fluxes of pathogens in streams. These models will assist in achieving a more ideal understanding of pathogen transport in the stream environment. Instead of assuming a constant or ignoring resuspension models should be able to provide variables for modeling and therefor understanding *E. coli* attachment and resuspension rates. By increasing the accuracy of models risk of gastrointestinal illness will be better understood.

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Appendix A Raw Data

Water Background

Table 1.1-Sediment-Water background for each bottom sediments including amounts of cfu/100 mL before and after inoculation

Date	Sediment	Average Depth of water 4.88m (in)	Depth of water averaged at 7.32m (in)	*E. coli* Average in TSB (CUF/ 100ml)	Sediment Before (cfu/ 100ml)	Sediment After (cfu/ 100ml)	Background H2O (cfu/ 100ml)	Sediment background (cfu/ 100ml)	Sediment Moisture Before (g)	Sediment Moisture After (g)	24 hours Sediment Moisture Before (g)	24 hours Sediment Moisture After (g)
6/9/2011	BF	5.465	6.29	NA	4.95E+03	N/A	N/A	NA	9.58	NA	6.443	NA
6/17/2011	BF	5.75	5.90625	NA	2.67E+03	2.67E+03	2.00E+01	-6.69E+05	1.03E+01	NA	9	NA
6/23/2011	BF	5.875	6.5	4.33E+11	1.68E+04	N/A	3.94E+02	NA	8.06	NA	6.2	NA
6/30/2011	BF	8.75	9.25	8.33E+10	3.40E+04	8.27E+03	4.40E+01	-4.71E+05	8.072	10.77	7.287	8.39
7/6/2011	BF	5.8125	6.5625	7.28E+12	2.35E+02	2.63E+05	1.33E+02	1.32E+05	30.475	23.663	NA	NA
7/13/2011	Sand	6.125	6.8125	5.33E+10	6.67E+01	1.60E+08	0.00E+00	1.59E+08	23.879	26.3	19.6	21.5
7/22/2011	Sand	6.5625	5.5625	1.92E+12	TMTC	6.64E+06	8.04E+03	6.08E+06	2.10E+01	2.08E+01	16.81	15.99
7/26/2011	Sand	8.75	8.75	3.77E+12	6.64E+06	1.60E+08	8.04E+03	1.59E+08	1.51E+01	1.53E+01	10.79	12.77
8/2/2011	Sand	5.625	6.5	2.87E+11	5.69E+05	7.71E+06	1.37E+03	6.30E+06	19.98	20.23	15.9	15.73
8/6/2011	SS	5.75	6.4375	7.50E+11	NA	1.50E+05	4.73E+02	-4.85E+05	15.19	15	12.82	12.86
8/23/2011	SS	5.25	6	9.83E+11	2.72E+07	1.76E+07	1.40E+02	1.72E+07	20.9	18.99	17.63	15.93
8/26/2011	SS	9	9.5	2.44E+14	7.22E+06	1.42E+07	1.33E+04	1.21E+07	20.7	17.35	17.53	15.27
9/1/2011	SS	5.5	6.25	3.35E+12	7.75E+06	1.60E+08	4.00E+00	1.59E+08	21.57	20.37	19.99	18.45

Depth Comparisons for Similar Flow Rates

Table 2.1 - Used for depth comparisons in SAS –Biofilm A

Sediment	Dates	Points	Depth (in)	Q (m3/s)	Time (min)	Attachment (Fraction)	*E. coli* (Average) (cfu/100 mL)	*E. coli* Background per time period (cfu/100 mL)	Resuspension U (cfu/m2/s)
BF	6/17/2011	4.88	5.83	1.46E-02	0	0.66	5.45E+05	3.66E+05	0.00E+00
BF	6/17/2011	4.88	5.83	1.46E-02	15	0.8	5.45E+05	4.08E+05	0.00E+00
BF	6/17/2011	4.88	5.83	1.46E-02	30	0.96	5.45E+05	1.00E+04	0.00E+00
BF	6/17/2011	4.88	5.83	1.46E-02	45	0.88	5.45E+05	2.06E+05	0.00E+00
BF	6/17/2011	4.88	5.83	1.46E-02	60	0.84	5.45E+05	2.92E+05	0.00E+00
BF	6/17/2011	7.32	5.83	1.46E-02	0	0	7.99E+05	3.66E+05	0.00E+00
BF	6/17/2011	7.32	5.83	1.46E-02	15	0.89	7.99E+05	4.08E+05	0.00E+00
BF	6/17/2011	7.32	5.83	1.46E-02	30	0.78	7.99E+05	1.00E+04	1.64E-08
BF	6/17/2011	7.32	5.83	1.46E-02	45	0.81	7.99E+05	2.06E+05	0.00E+00
BF	6/17/2011	7.32	5.83	1.46E-02	60	0.8	7.99E+05	2.92E+05	0.00E+00
BF	6/30/2011	4.88	9	1.45E-02	0	0.19	4.23E+05	2.65E+05	7.24E-06
BF	6/30/2011	4.88	9	1.45E-02	15	0.41	4.23E+05	2.09E+05	1.66E-06
BF	6/30/2011	4.88	9	1.45E-02	30	0.31	4.23E+05	2.33E+05	6.19E-06
BF	6/30/2011	4.88	9	1.45E-02	45	0	4.23E+05	2.51E+05	1.14E-05
BF	6/30/2011	4.88	9	1.45E-02	60	0	4.23E+05	3.16E+05	6.06E-06
BF	6/30/2011	7.32	9	1.45E-02	0	0	5.36E+05	2.65E+05	5.51E-05
BF	6/30/2011	7.32	9	1.45E-02	15	0.6	5.36E+05	2.09E+05	0.00E+00
BF	6/30/2011	7.32	9	1.45E-02	30	0.16	5.36E+05	2.33E+05	0.00E+00
BF	6/30/2011	7.32	9	1.45E-02	45	0.63	5.36E+05	2.51E+05	0.00E+00
BF	6/30/2011	7.32	9	1.45E-02	60	0	5.36E+05	3.16E+05	1.17E-05

Table 2.2 - Used for depth comparisons in SAS –Biofilm B

Sediment	Dates	Resuspension A (cfu/m2/s)	Total Resuspension (cfu/m2/s)	Turbidity (NTU)	LISST, Sizes (micrometers)	*E. coli* Sediment Before Inoculation (cfu/100mL)	*E. coli* Sediment After (cfu/100mL)	Average Attached Composite Concentrations (cfu/100ml)
BF	6/17/2011	4.21E-06	4.21E-06	19.73	NA	2.67E+03	2.67E+03	8.58E+04
BF	6/17/2011	9.06E-06	9.06E-06	19.73	NA	2.67E+03	2.67E+03	1.85E+05
BF	6/17/2011	1.08E-05	1.08E-05	19.73	NA	2.67E+03	2.67E+03	2.19E+05
BF	6/17/2011	4.59E-06	4.59E-06	19.73	NA	2.67E+03	2.67E+03	9.37E+04
BF	6/17/2011	3.96E-06	3.96E-06	19.73	NA	2.67E+03	2.67E+03	8.07E+04
BF	6/17/2011	-8.42E-06	-8.42E-06	18.95	46.32	2.67E+03	2.67E+03	0.00E+00
BF	6/17/2011	-1.50E-05	-1.50E-05	18.95	46.32	2.67E+03	2.67E+03	3.15E+04
BF	6/17/2011	-1.79E-05	-1.79E-05	18.95	46.32	2.67E+03	2.67E+03	3.63E+04
BF	6/17/2011	-6.15E-06	-6.15E-06	18.95	46.32	2.67E+03	2.67E+03	3.10E+04
BF	6/17/2011	-4.11E-06	-4.11E-06	18.95	46.32	2.67E+03	2.67E+03	3.88E+04
BF	6/30/2011	4.73E-06	1.20E-05	29.58	NA	3.40E+04	8.27E+03	9.67E+04
BF	6/30/2011	8.15E-06	9.81E-06	29.58	NA	3.40E+04	8.27E+03	1.67E+05
BF	6/30/2011	7.99E-06	1.42E-05	29.58	NA	3.40E+04	8.27E+03	1.63E+05
BF	6/30/2011	0.00E+00	1.14E-05	29.58	NA	3.40E+04	8.27E+03	0.00E+00
BF	6/30/2011	0.00E+00	6.06E-06	29.58	NA	3.40E+04	8.27E+03	0.00E+00
BF	6/30/2011	-9.46E-06	4.56E-05	25.11	21.53	3.40E+04	8.27E+03	0.00E+00
BF	6/30/2011	5.87E-06	5.87E-06	25.11	21.53	3.40E+04	8.27E+03	2.27E+05
BF	6/30/2011	-1.04E-05	-1.04E-05	25.11	21.53	3.40E+04	8.27E+03	5.67E+04
BF	6/30/2011	3.00E-05	3.00E-05	25.11	21.53	3.40E+04	8.27E+03	1.67E+05
BF	6/30/2011	0.00E+00	1.17E-05	25.11	21.53	3.40E+04	8.27E+03	0.00E+00

Table 2.3 - Used for depth comparisons in SAS –Biofilm C

Sediment	Dates	Log (Average Attached)	Turbidity per time Composites (NTU)	*E. coli* for time periods (cfu/100 mL)	Log (*E. coli*)	Depth 2 (cm)	Average unattached Composite Concentrations (cfu/100ml)	Log (Average unattached)	H20 Background (cfu/100mL)
BF	6/17/2011	4.93E+00	18.5	6.08E+05	5.78	15.2	44000	4.64	2.00E+01
BF	6/17/2011	5.27E+00	17.6	4.52E+05	5.66	15.2	45500	4.66	2.00E+01
BF	6/17/2011	5.34E+00	17.9	5.18E+05	5.71	15.2	9833	3.99	2.00E+01
BF	6/17/2011	4.97E+00	15.5	5.73E+05	5.76	15.2	13167	4.12	2.00E+01
BF	6/17/2011	4.91E+00	18.5	5.72E+05	5.76	15.2	15333	4.19	2.00E+01
BF	6/17/2011	0.00E+00	21.7	9.62E+05	5.98	15.2	13500	4.13	2.00E+01
BF	6/17/2011	4.50E+00	18.9	7.69E+05	5.89	15.2	3833	3.58	2.00E+01
BF	6/17/2011	4.56E+00	18.2	7.94E+05	5.9	15.2	10000	4	2.00E+01
BF	6/17/2011	4.49E+00	20.1	7.82E+05	5.89	15.2	7167	3.86	2.00E+01
BF	6/17/2011	4.59E+00	21.4	1.15E+06	6.06	15.2	9500	3.98	2.00E+01
BF	6/30/2011	4.99E+00	32.5	5.71E+05	5.76	22.9	413333	5.62	4.40E+01
BF	6/30/2011	5.22E+00	30.6	5.32E+05	5.73	22.9	243333	5.39	4.40E+01
BF	6/30/2011	5.21E+00	32.1	5.67E+05	5.75	22.9	360000	5.56	4.40E+01
BF	6/30/2011	0.00E+00	31.4	6.18E+05	5.79	22.9	483333	5.68	4.40E+01
BF	6/30/2011	0.00E+00	27.8	5.90E+05	5.77	22.9	440000	5.64	4.40E+01
BF	6/30/2011	0.00E+00	32.5	7.54E+05	5.88	22.9	976667	5.99	4.40E+01
BF	6/30/2011	5.36E+00	30.6	7.50E+05	5.88	22.9	150000	5.18	4.40E+01
BF	6/30/2011	4.75E+00	32.1	7.52E+05	5.88	22.9	306667	5.49	4.40E+01
BF	6/30/2011	5.22E+00	31.4	7.43E+05	5.87	22.9	96667	4.99	4.40E+01
BF	6/30/2011	0.00E+00	27.8	9.01E+05	5.95	22.9	560000	5.75	4.40E+01

Table 3.1 - Used for depth comparisons in SAS –Sand A

Sediment	Dates	Points	Depth (in)	Q (m3/s)	Time (min)	Attachment (Fraction)	*E. coli* (Average) (cfu/100 mL)	*E. coli* Background per time period (cfu/100 mL)	Resuspension U (cfu/m2/s)
Sand	7/13/2011	4.88	6.47	4.45E-03	0	0.16	5.12E+05	5.30E+05	0.00E+00
Sand	7/13/2011	4.88	6.47	4.45E-03	15	0.34	5.12E+05	4.71E+05	0.00E+00
Sand	7/13/2011	4.88	6.47	4.45E-03	30	0.05	5.12E+05	4.62E+05	0.00E+00
Sand	7/13/2011	4.88	6.47	4.45E-03	45	0.07	5.12E+05	5.36E+05	0.00E+00
Sand	7/13/2011	4.88	6.47	4.45E-03	60	0.13	5.12E+05	4.65E+05	0.00E+00
Sand	7/13/2011	7.32	6.47	4.45E-03	0	0.24	3.71E+05	5.30E+05	0.00E+00
Sand	7/13/2011	7.32	6.47	4.45E-03	15	0.1	3.71E+05	4.71E+05	1.95E-07
Sand	7/13/2011	7.32	6.47	4.45E-03	30	0.08	3.71E+05	4.62E+05	1.25E-07
Sand	7/13/2011	7.32	6.47	4.45E-03	45	0.09	3.71E+05	5.36E+05	0.00E+00
Sand	7/13/2011	7.32	6.47	4.45E-03	60	0.1	3.71E+05	4.65E+05	1.54E-06
Sand	7/26/2011	4.88	8.75	4.56E-03	0	0.16	3.54E+05	3.71E+05	0.00E+00
Sand	7/26/2011	4.88	8.75	4.56E-03	15	0	3.54E+05	3.51E+05	5.11E-09
Sand	7/26/2011	4.88	8.75	4.56E-03	30	0.15	3.54E+05	3.66E+05	0.00E+00
Sand	7/26/2011	4.88	8.75	4.56E-03	45	0	3.54E+05	4.37E+05	0.00E+00
Sand	7/26/2011	4.88	8.75	4.56E-03	60	0	3.54E+05	4.14E+05	0.00E+00
Sand	7/26/2011	7.32	8.75	4.56E-03	0	0	3.61E+05	3.71E+05	1.66E-06
Sand	7/26/2011	7.32	8.75	4.56E-03	15	0	3.61E+05	3.51E+05	0.00E+00
Sand	7/26/2011	7.32	8.75	4.56E-03	30	0	3.61E+05	3.66E+05	0.00E+00
Sand	7/26/2011	7.32	8.75	4.56E-03	45	0.12	3.61E+05	4.37E+05	0.00E+00
Sand	7/26/2011	7.32	8.75	4.56E-03	60	0.03	3.61E+05	4.14E+05	0.00E+00

Table 3.2 - Used for depth comparisons in SAS –Sand B

Sediment	Dates	Resuspension A (cfu/m2/s)	Total Resuspension (cfu/m2/s)	Turbidity (NTU)	LISST, Sizes (micrometers)	*E. coli* Sediment Before Inoculation (cfu/100mL)	*E. coli* Sediment After (cfu/100mL)	Average Attached Composite Concentrations (cfu/100ml)
Sand	7/13/2011	1.18E-06	1.18E-06	6.13	NA	6.77E+01	1.60E+08	7.90E+04
Sand	7/13/2011	2.69E-06	2.69E-06	6.13	NA	6.77E+01	1.60E+08	1.80E+05
Sand	7/13/2011	3.12E-07	3.12E-07	6.13	NA	6.77E+01	1.60E+08	2.08E+04
Sand	7/13/2011	4.29E-07	4.29E-07	6.13	NA	6.77E+01	1.60E+08	2.87E+04
Sand	7/13/2011	9.53E-07	9.53E-07	6.13	NA	6.77E+01	1.60E+08	6.37E+04
Sand	7/13/2011	1.05E-06	1.05E-06	4.95	15.81	6.67E+01	1.60E+08	1.14E+05
Sand	7/13/2011	-4.22E-06	-4.02E-06	4.95	15.81	6.67E+01	1.60E+08	3.88E+04
Sand	7/13/2011	5.34E-07	6.59E-07	4.95	15.81	6.67E+01	1.60E+08	3.87E+04
Sand	7/13/2011	1.95E-07	1.95E-07	4.95	15.81	6.67E+01	1.60E+08	3.52E+04
Sand	7/13/2011	-3.99E-07	1.14E-06	4.95	15.81	6.67E+01	1.60E+08	5.03E+04
Sand	7/26/2011	9.55E-07	9.55E-07	2.17	NA	6.64E+06	1.60E+08	6.23E+04
Sand	7/26/2011	1.53E-08	2.04E-08	2.17	NA	6.64E+06	1.60E+08	1.00E+03
Sand	7/26/2011	1.01E-06	1.01E-06	2.17	NA	6.64E+06	1.60E+08	6.60E+04
Sand	7/26/2011	-3.86E-07	-3.86E-07	2.17	NA	6.64E+06	1.60E+08	0.00E+00
Sand	7/26/2011	-1.47E-06	-1.47E-06	2.17	NA	6.64E+06	1.60E+08	0.00E+00
Sand	7/26/2011	0.00E+00	1.66E-06	2.26	26.94	6.64E+06	1.60E+08	0.00E+00
Sand	7/26/2011	0.00E+00	0.00E+00	2.26	26.94	6.64E+06	1.60E+08	0.00E+00
Sand	7/26/2011	0.00E+00	0.00E+00	2.26	26.94	6.64E+06	1.60E+08	0.00E+00
Sand	7/26/2011	1.53E-06	1.53E-06	2.26	26.94	6.64E+06	1.60E+08	5.00E+04
Sand	7/26/2011	3.27E-07	3.27E-07	2.26	26.94	6.64E+06	1.60E+08	1.07E+04

Table 3.3 - Used for depth comparisons in SAS –Sand C

Sediment	Dates	Log (Average Attached)	Turbidity per time Composites (NTU)	*E. coli* for time periods (cfu/100 mL)	Log (*E. coli*)	Depth 2 (cm)	Average unattached Composite Concentrations (cfu/100ml)	Log (Average unattached)	H20 Background (cfu/100mL)
Sand	7/13/2011	4.90E+00	4.48	5.05E+05	5.7	15.2	412333	5.62	0.00E+00
Sand	7/13/2011	5.25E+00	4.9	5.33E+05	5.73	15.2	355000	5.55	0.00E+00
Sand	7/13/2011	4.32E+00	5.92	5.08E+05	5.71	15.2	422167	5.63	0.00E+00
Sand	7/13/2011	4.46E+00	4.26	5.14E+05	5.71	15.2	401833	5.6	0.00E+00
Sand	7/13/2011	4.80E+00	4.57	4.99E+05	5.7	15.2	419667	5.62	0.00E+00
Sand	7/13/2011	5.06E+00	4.75	3.93E+05	5.59	15.2	359333	5.56	0.00E+00
Sand	7/13/2011	4.59E+00	5.01	3.76E+05	5.57	15.2	361500	5.56	0.00E+00
Sand	7/13/2011	4.59E+00	4.32	3.77E+05	5.58	15.2	426333	5.63	0.00E+00
Sand	7/13/2011	4.55E+00	5.36	3.59E+05	5.55	15.2	368333	5.57	0.00E+00
Sand	7/13/2011	4.70E+00	3.73	3.53E+05	5.55	15.2	471000	5.67	0.00E+00
Sand	7/26/2011	4.79E+00	3.23	3.54E+05	5.55	22.9	325333	5.51	8.04E+03
Sand	7/26/2011	3.00E+00	2.87	4.13E+05	5.62	22.9	351333	5.55	8.04E+03
Sand	7/26/2011	4.82E+00	2.93	3.28E+05	5.52	22.9	361333	5.56	8.04E+03
Sand	7/26/2011	0.00E+00	2.63	3.10E+05	5.49	22.9	387000	5.59	8.04E+03
Sand	7/26/2011	0.00E+00	2.7	3.62E+05	5.56	22.9	378000	5.58	8.04E+03
Sand	7/26/2011	0.00E+00	2.66	3.37E+05	5.53	22.9	379333	5.58	8.04E+03
Sand	7/26/2011	0.00E+00	2.47	3.68E+05	5.57	22.9	345333	5.54	8.04E+03
Sand	7/26/2011	0.00E+00	2.48	3.52E+05	5.55	22.9	318333	5.5	8.04E+03
Sand	7/26/2011	4.70E+00	2.3	3.35E+05	5.52	22.9	380000	5.58	8.04E+03
Sand	7/26/2011	4.03E+00	2.48	3.71E+05	5.57	22.9	362000	5.56	8.04E+03

Table 4.1 - Used for depth comparisons in SAS –Sand-Silt A

Sediment	Dates	Points	Depth	Q	Time	Attachment (fraction)	*E. coli* (cfu/100 mL) (average For all time Periods)	*E. coli* Background In water per time period	Resuspension U
SS	8/23/2011	4.88	5.625	2.45E-03	0	0	3.63E+05	1.00E+04	2.74E-07
SS	8/23/2011	4.88	5.625	2.45E-03	15	0.46087	3.63E+05	4.40E+05	0.00E+00
SS	8/23/2011	4.88	5.625	2.45E-03	30	0.669173	3.63E+05	4.53E+05	0.00E+00
SS	8/23/2011	4.88	5.625	2.45E-03	45	0.370861	3.63E+05	4.97E+05	0.00E+00
SS	8/23/2011	4.88	5.625	2.45E-03	60	0.279762	3.63E+05	4.57E+05	0.00E+00
SS	8/23/2011	7.32	5.625	2.45E-03	0	0.333333	3.96E+05	1.00E+04	3.84E-07
SS	8/23/2011	7.32	5.625	2.45E-03	15	0.16	3.96E+05	4.40E+05	2.36E-06
SS	8/23/2011	7.32	5.625	2.45E-03	30	0.708772	3.96E+05	4.53E+05	2.14E-06
SS	8/23/2011	7.32	5.625	2.45E-03	45	0	3.96E+05	4.97E+05	1.15E-06
SS	8/23/2011	7.32	5.625	2.45E-03	60	0.218487	3.96E+05	4.57E+05	0.00E+00
SS	8/26/2011	4.88	9.25	3.14E-03	0	0.582192	1.47E+06	1.04E+06	1.93E-06
SS	8/26/2011	4.88	9.25	3.14E-03	15	0.469388	1.47E+06	8.40E+05	2.11E-06
SS	8/26/2011	4.88	9.25	3.14E-03	30	0.093137	1.47E+06	8.53E+05	1.05E-05
SS	8/26/2011	4.88	9.25	3.14E-03	45	0.40873	1.47E+06	1.71E+06	0.00E+00
SS	8/26/2011	4.88	9.25	3.14E-03	60	0.473077	1.47E+06	1.83E+06	0.00E+00
SS	8/26/2011	7.32	9.25	3.14E-03	0	0.06875	2.68E+06	1.04E+06	5.70E-06
SS	8/26/2011	7.32	9.25	3.14E-03	15	0.372549	2.68E+06	8.40E+05	5.06E-06
SS	8/26/2011	7.32	9.25	3.14E-03	30	0.743304	2.68E+06	8.53E+05	0.00E+00
SS	8/26/2011	7.32	9.25	3.14E-03	45	0.75	2.68E+06	1.71E+06	0.00E+00
SS	8/26/2011	7.32	9.25	3.14E-03	60	0.337209	2.68E+06	1.83E+06	0.00E+00

Table 4.2 - Used for depth comparisons in SAS –Sand-Silt B

Sediment	Dates	Resuspension A (cfu/m2/s)	Total Resuspension (cfu/m2/s)	Turbidity (NTU)	LISST, Sizes (micrometers)	*E. coli* Sediment Before Inoculation (cfu/100mL)	*E. coli* Sediment After (cfu/100mL)	Average Attached Composite Concentrations (cfu/100ml)
SS	8/23/2011	-1.37E-07	1.37E-07	1.25	NA	2.72E+07	1.76E+07	0.00E+00
SS	8/23/2011	1.45E-06	1.45E-06	1.25	NA	2.72E+07	1.76E+07	1.77E+05
SS	8/23/2011	2.44E-06	2.44E-06	1.25	NA	2.72E+07	1.76E+07	2.97E+05
SS	8/23/2011	1.54E-06	1.54E-06	1.25	NA	2.72E+07	1.76E+07	1.87E+05
SS	8/23/2011	1.29E-06	1.29E-06	1.25	NA	2.72E+07	1.76E+07	1.57E+05
SS	8/23/2011	8.23E-07	1.21E-06	1.06	14.64	2.72E+07	1.76E+07	3.33E+04
SS	8/23/2011	-1.81E-06	5.48E-07	1.06	14.64	2.72E+07	1.76E+07	6.67E+04
SS	8/23/2011	6.20E-06	8.34E-06	1.06	14.64	2.72E+07	1.76E+07	6.73E+05
SS	8/23/2011	-3.18E-06	-2.03E-06	1.06	14.64	2.72E+07	1.76E+07	0.00E+00
SS	8/23/2011	-1.15E-06	-1.15E-06	1.06	14.64	2.72E+07	1.76E+07	8.67E+04
SS	8/26/2011	1.79E-05	1.99E-05	2.27	NA	7.22E+06	1.42E+07	1.70E+06
SS	8/26/2011	9.70E-06	1.18E-05	2.27	NA	7.22E+06	1.42E+07	9.20E+05
SS	8/26/2011	2.00E-06	1.25E-05	2.27	NA	7.22E+06	1.42E+07	1.90E+05
SS	8/26/2011	1.09E-05	1.09E-05	2.27	NA	7.22E+06	1.42E+07	1.03E+06
SS	8/26/2011	1.30E-05	1.30E-05	2.27	NA	7.22E+06	1.42E+07	1.23E+06
SS	8/26/2011	-2.34E-05	-1.77E-05	1.37	8.06	7.22E+06	1.42E+07	1.10E+05
SS	8/26/2011	-5.91E-06	-8.44E-07	1.37	8.06	7.22E+06	1.42E+07	7.60E+05
SS	8/26/2011	3.12E-05	3.12E-05	1.37	8.06	7.22E+06	1.42E+07	3.33E+06
SS	8/26/2011	4.90E-05	4.90E-05	1.37	8.06	7.22E+06	1.42E+07	3.81E+06
SS	8/26/2011	-1.67E-05	-1.67E-05	1.37	8.06	7.22E+06	1.42E+07	5.80E+05

Table 4.3 - Used for depth comparisons in SAS –Sand-Silt C

Sediment	Dates	Log (Average Attached)	Turbidity per time Composites (NTU)	*E. coli* for time periods (cfu/100 mL)	Log (*E. coli*)	Depth 2 (cm)	Average unattached Composite Concentrations (cfu/100ml)	Log (Average unattached)	H20 Background (cfu/100mL)
SS	8/23/2011	0.00E+00	3.16	1.81E+04	4.26	15.2	43333	4.64	1.40E+02
SS	8/23/2011	5.25E+00	3.16	4.21E+05	5.62	15.2	206667	5.32	1.40E+02
SS	8/23/2011	5.47E+00	3.95	4.92E+05	5.69	15.2	146667	5.17	1.40E+02
SS	8/23/2011	5.27E+00	4.13	4.08E+05	5.61	15.2	316667	5.5	1.40E+02
SS	8/23/2011	5.19E+00	4.42	4.76E+05	5.68	15.2	403333	5.61	1.40E+02
SS	8/23/2011	4.52E+00	2.25	4.09E+04	4.61	15.2	66667	4.82	1.40E+02
SS	8/23/2011	4.82E+00	2.17	4.76E+05	5.68	15.2	350000	5.54	1.40E+02
SS	8/23/2011	5.83E+00	2.62	4.62E+05	5.66	15.2	276667	5.44	1.40E+02
SS	8/23/2011	0.00E+00	3.58	5.19E+05	5.71	15.2	386667	5.59	1.40E+02
SS	8/23/2011	4.94E+00	3.65	4.83E+05	5.68	15.2	310000	5.49	1.40E+02
SS	8/26/2011	6.23E+00	8.04	1.42E+06	6.15	22.9	1220000	6.09	1.33E+04
SS	8/26/2011	5.96E+00	6.38	1.31E+06	6.12	22.9	1040000	6.02	1.33E+04
SS	8/26/2011	5.28E+00	13.7	1.64E+06	6.22	22.9	1850000	6.27	1.33E+04
SS	8/26/2011	6.01E+00	8.66	1.39E+06	6.14	22.9	1490000	6.17	1.33E+04
SS	8/26/2011	6.09E+00	14.7	1.60E+06	6.21	22.9	1370000	6.14	1.33E+04
SS	8/26/2011	5.04E+00	8.72	2.69E+06	6.43	22.9	1490000	6.17	1.33E+04
SS	8/26/2011	5.88E+00	10.4	2.56E+06	6.41	22.9	1280000	6.11	1.33E+04
SS	8/26/2011	6.52E+00	9	2.39E+06	6.38	22.9	1150000	6.06	1.33E+04
SS	8/26/2011	6.58E+00	8.55	3.10E+06	6.49	22.9	1270000	6.1	1.33E+04
SS	8/26/2011	5.76E+00	10.7	2.68E+06	6.43	22.9	1140000	6.06	1.33E+04

Flow and Bottom sediments Comparisons of Single Depths

Table 5.1- Used for comparisons in SAS –Biofilm A

Sediment	Dates	Points	Depth (in)	Q (m^3/s)	Time (min)	Attachment (Fraction)	*E. coli* (cfu/100 mL) (time Periods)	*E. coli* Background In water per time period	Resuspension U ($cfu/m^2/s$)
BF	6/9/2011	4.88	5.88	1.42E-02	0	0.38	1.92E+05	7.80E+04	2.80E-06
BF	6/9/2011	4.88	5.88	1.42E-02	15	0.51	1.92E+05	4.40E+04	3.57E-06
BF	6/9/2011	4.88	5.88	1.42E-02	30	0.56	1.92E+05	5.10E+04	2.52E-06
BF	6/9/2011	4.88	5.88	1.42E-02	45	0.52	1.92E+05	5.70E+04	2.32E-06
BF	6/9/2011	4.88	5.88	1.42E-02	60	0.76	1.92E+05	7.40E+04	0.00E+00
BF	6/9/2011	7.32	5.88	1.42E-02	0	0.47	1.86E+05	7.80E+04	0.00E+00
BF	6/9/2011	7.32	5.88	1.42E-02	15	0.11	1.86E+05	4.40E+04	1.87E-06
BF	6/9/2011	7.32	5.88	1.42E-02	30	0.42	1.86E+05	5.10E+04	1.36E-06
BF	6/9/2011	7.32	5.88	1.42E-02	45	0.28	1.86E+05	5.70E+04	1.71E-06
BF	6/9/2011	7.32	5.88	1.42E-02	60	0.35	1.86E+05	7.40E+04	5.88E-06
BF	6/17/2011	4.88	5.83	1.46E-02	0	0.66	5.45E+05	3.66E+05	0.00E+00
BF	6/17/2011	4.88	5.83	1.46E-02	15	0.8	5.45E+05	4.08E+05	0.00E+00
BF	6/17/2011	4.88	5.83	1.46E-02	30	0.96	5.45E+05	1.00E+04	0.00E+00
BF	6/17/2011	4.88	5.83	1.46E-02	45	0.88	5.45E+05	2.06E+05	0.00E+00
BF	6/17/2011	4.88	5.83	1.46E-02	60	0.84	5.45E+05	2.92E+05	0.00E+00
BF	6/17/2011	7.32	5.83	1.46E-02	0	0	7.99E+05	3.66E+05	0.00E+00
BF	6/17/2011	7.32	5.83	1.46E-02	15	0.89	7.99E+05	4.08E+05	0.00E+00
BF	6/17/2011	7.32	5.83	1.46E-02	30	0.78	7.99E+05	1.00E+04	1.64E-08
BF	6/17/2011	7.32	5.83	1.46E-02	45	0.81	7.99E+05	2.06E+05	0.00E+00
BF	6/17/2011	7.32	5.83	1.46E-02	60	0.8	7.99E+05	2.92E+05	0.00E+00
BF	6/23/2011	4.88	6.19	1.26E-02	0	0.24	1.00E+06	1.05E+06	0.00E+00
BF	6/23/2011	4.88	6.19	1.26E-02	15	0.14	1.00E+06	8.40E+05	4.76E-06
BF	6/23/2011	4.88	6.19	1.26E-02	30	0.57	1.00E+06	7.93E+05	0.00E+00
BF	6/23/2011	4.88	6.19	1.26E-02	45	0.35	1.00E+06	1.03E+06	0.00E+00

Table 5.1 Continued									
BF	6/23/2011	4.88	6.19	1.26E-02	60	0.44	1.00E+06	1.16E+06	0.00E+00
BF	6/23/2011	7.32	6.19	1.26E-02	0	0	1.11E+06	1.05E+06	0.00E+00
BF	6/23/2011	7.32	6.19	1.26E-02	15	0.2	1.11E+06	8.40E+05	0.00E+00
BF	6/23/2011	7.32	6.19	1.26E-02	30	0	1.11E+06	7.93E+05	1.58E-05
BF	6/23/2011	7.32	6.19	1.26E-02	45	0	1.11E+06	1.03E+06	4.38E-07
BF	6/23/2011	7.32	6.19	1.26E-02	60	0.21	1.11E+06	1.16E+06	0.00E+00
BF	7/6/2011	4.88	6.19	1.61E-02	0	0.33	1.37E+05	1.12E+05	0.00E+00
BF	7/6/2011	4.88	6.19	1.61E-02	15	0.13	1.37E+05	1.39E+05	0.00E+00
BF	7/6/2011	4.88	6.19	1.61E-02	30	0.2	1.37E+05	1.08E+05	1.26E-07
BF	7/6/2011	4.88	6.19	1.61E-02	45	0	1.37E+05	1.10E+05	1.22E-05
BF	7/6/2011	4.88	6.19	1.61E-02	60	0.08	1.37E+05	1.29E+05	0.00E+00
BF	7/6/2011	7.32	6.19	1.61E-02	0	0.04	1.25E+05	1.12E+05	4.34E-06
BF	7/6/2011	7.32	6.19	1.61E-02	15	0	1.25E+05	1.39E+05	1.80E-07
BF	7/6/2011	7.32	6.19	1.61E-02	30	0	1.25E+05	1.08E+05	3.31E-06
BF	7/6/2011	7.32	6.19	1.61E-02	45	0	1.25E+05	1.10E+05	0.00E+00
BF	7/6/2011	7.32	6.19	1.61E-02	60	0.16	1.25E+05	1.29E+05	7.20E-07

Table 5.2 - Used for comparisons in SAS –Biofilm B

Sediment	Dates	Resuspension A (cfu/m^2/s)	Total Resuspension (cfu/m^2/s)	Turbidity (NTU)	LISST, Sizes (micro)	*E. coli* Sediment Before (cfu)	*E. coli* Sediment After (cfu)	Average Attached Composite Concentrations (cfu/100ml)
BF	6/9/2011	4.03E-06	6.83E-06	11.33	NA	4.95E+03	0	8.42E+04
BF	6/9/2011	5.92E-06	9.49E-06	11.33	NA	4.95E+03	0	1.24E+05
BF	6/9/2011	6.31E-06	8.83E-06	11.33	NA	4.95E+03	0	1.32E+05
BF	6/9/2011	5.39E-06	7.70E-06	11.33	NA	4.95E+03	0	1.13E+05
BF	6/9/2011	1.04E-05	1.04E-05	11.33	NA	4.95E+03	0	2.17E+05
BF	6/9/2011	1.37E-06	1.37E-06	14.20	46.32	4.95E+03	0	9.85E+04
BF	6/9/2011	-1.02E-05	-8.29E-06	14.20	46.32	4.95E+03	0	1.77E+04
BF	6/9/2011	-4.55E-06	-3.19E-06	14.20	46.32	4.95E+03	0	8.42E+04
BF	6/9/2011	-6.21E-06	-4.50E-06	14.20	46.32	4.95E+03	0	4.77E+04
BF	6/9/2011	-1.42E-05	-8.31E-06	14.20	46.32	4.95E+03	0	6.92E+04
BF	6/17/2011	4.21E-06	4.21E-06	19.73	NA	2.67E+03	2.67E+03	8.58E+04
BF	6/17/2011	9.06E-06	9.06E-06	19.73	NA	2.67E+03	2.67E+03	1.85E+05
BF	6/17/2011	1.08E-05	1.08E-05	19.73	NA	2.67E+03	2.67E+03	2.19E+05
BF	6/17/2011	4.59E-06	4.59E-06	19.73	NA	2.67E+03	2.67E+03	9.37E+04
BF	6/17/2011	3.96E-06	3.96E-06	19.73	NA	2.67E+03	2.67E+03	8.07E+04
BF	6/17/2011	-8.42E-06	-8.42E-06	18.95	46.32	2.67E+03	2.67E+03	0.00E+00
BF	6/17/2011	-1.50E-05	-1.50E-05	18.95	46.32	2.67E+03	2.67E+03	3.15E+04
BF	6/17/2011	-1.79E-05	-1.79E-05	18.95	46.32	2.67E+03	2.67E+03	3.63E+04
BF	6/17/2011	-6.15E-06	-6.15E-06	18.95	46.32	2.67E+03	2.67E+03	3.10E+04
BF	6/17/2011	-4.11E-06	-4.11E-06	18.95	46.32	2.67E+03	2.67E+03	3.88E+04
BF	6/23/2011	1.14E-05	1.14E-05	14.22	NA	1.68E+04	0	2.70E+05
BF	6/23/2011	6.74E-06	1.15E-05	14.22	NA	1.68E+04	0	1.59E+05
BF	6/23/2011	3.22E-05	3.22E-05	14.22	NA	1.68E+04	0	7.61E+05
BF	6/23/2011	1.67E-05	1.67E-05	14.22	NA	1.68E+04	0	3.95E+05
BF	6/23/2011	1.98E-05	1.98E-05	14.22	NA	1.68E+04	0	4.66E+05

Table 5.2 Continued

BF	6/23/2011	-2.29E-05	-2.29E-05	14.50	60.5	1.68E+04	0	0.00E+00
BF	6/23/2011	4.24E-08	4.24E-08	14.50	60.5	1.68E+04	0	1.60E+05
BF	6/23/2011	-6.45E-05	-4.87E-05	14.50	60.5	1.68E+04	0	0.00E+00
BF	6/23/2011	-3.34E-05	-3.30E-05	14.50	60.5	1.68E+04	0	0.00E+00
BF	6/23/2011	-2.87E-05	-2.87E-05	14.50	60.5	1.68E+04	0	1.28E+05
BF	7/6/2011	2.79E-06	2.79E-06	51.32	NA	2.35E+02	2.63E+05	5.17E+04
BF	7/6/2011	9.00E-07	9.00E-07	51.32	NA	2.35E+02	2.63E+05	1.67E+04
BF	7/6/2011	1.50E-06	1.63E-06	51.32	NA	2.35E+02	2.63E+05	2.78E+04
BF	7/6/2011	0.00E+00	1.22E-05	51.32	NA	2.35E+02	2.63E+05	0.00E+00
BF	7/6/2011	5.13E-07	5.13E-07	51.32	NA	2.35E+02	2.63E+05	9.50E+03
BF	7/6/2011	1.06E-05	1.50E-05	39.80	15.65	2.35E+02	2.63E+05	5.83E+03
BF	7/6/2011	3.09E-06	3.27E-06	39.80	15.65	2.35E+02	2.63E+05	0.00E+00
BF	7/6/2011	1.22E-05	1.55E-05	39.80	15.65	2.35E+02	2.63E+05	0.00E+00
BF	7/6/2011	3.36E-05	3.36E-05	39.80	15.65	2.35E+02	2.63E+05	0.00E+00
BF	7/6/2011	1.42E-05	1.49E-05	39.80	15.65	2.35E+02	2.63E+05	2.32E+04

Table 5.3- Used for comparisons in SAS –Biofilm C

Sediment	Dates	Log(Average Attached Composites)	Turbidity per Time Composites	*E. coli* For each time period (cfu/100 mL)	Log (*E. coli*)	Depth 2 (cm)	Average unattached Composite Concentrations (cfu/100ml)	Log(Average unattached)	H20 Background (cfu/100mL)
BF	6/9/2011	4.93E+00	15.2	1.86E+05	5.27	15.2	136500	5.14	NA
BF	6/9/2011	5.09E+00	16.7	1.73E+05	5.24	15.2	118500	5.07	NA
BF	6/9/2011	5.12E+00	13.2	2.14E+05	5.33	15.2	103667	5.02	NA
BF	6/9/2011	5.05E+00	11.9	1.94E+05	5.29	15.2	105333	5.02	NA
BF	6/9/2011	5.34E+00	15.8	2.06E+05	5.31	15.2	68333	4.83	NA
BF	6/9/2011	4.99E+00	18.5	1.75E+05	5.24	15.2	110667	5.04	NA
BF	6/9/2011	4.25E+00	16.4	1.92E+05	5.28	15.2	138000	5.14	NA
BF	6/9/2011	4.93E+00	17.4	1.82E+05	5.26	15.2	117833	5.07	NA
BF	6/9/2011	4.68E+00	18.5	2.07E+05	5.32	15.2	123167	5.09	NA
BF	6/9/2011	4.84E+00	18.6	1.73E+05	5.24	15.2	129667	5.11	NA
BF	6/17/2011	4.93E+00	18.5	6.08E+05	5.78	15.2	44000	4.64	2.00E+01
BF	6/17/2011	5.27E+00	17.6	4.52E+05	5.66	15.2	45500	4.66	2.00E+01
BF	6/17/2011	5.34E+00	17.9	5.18E+05	5.71	15.2	9833	3.99	2.00E+01
BF	6/17/2011	4.97E+00	15.5	5.73E+05	5.76	15.2	13167	4.12	2.00E+01
BF	6/17/2011	4.91E+00	18.5	5.72E+05	5.76	15.2	15333	4.19	2.00E+01
BF	6/17/2011	0.00E+00	21.7	9.62E+05	5.98	15.2	13500	4.13	2.00E+01
BF	6/17/2011	4.50E+00	18.9	7.69E+05	5.89	15.2	3833	3.58	2.00E+01
BF	6/17/2011	4.56E+00	18.2	7.94E+05	5.9	15.2	10000	4	2.00E+01
BF	6/17/2011	4.49E+00	20.1	7.82E+05	5.89	15.2	7167	3.86	2.00E+01
BF	6/17/2011	4.59E+00	21.4	1.15E+06	6.06	15.2	9500	3.98	2.00E+01
BF	6/23/2011	5.43E+00	15.5	1.07E+06	6.03	15.2	872667	5.94	3.94E+02
BF	6/23/2011	5.20E+00	16.2	1.04E+06	6.02	15.2	952333	5.98	3.94E+02
BF	6/23/2011	5.88E+00	15.4	9.29E+05	5.97	15.2	575333	5.76	3.94E+02
BF	6/23/2011	5.60E+00	14.3	1.03E+06	6.01	15.2	741500	5.87	3.94E+02

Table 5.3 Continued									
BF	6/23/2011	5.67E+00	13	9.37E+05	5.97	15.2	592000	5.77	3.94E+02
BF	6/23/2011	0.00E+00	14.7	1.18E+06	6.07	15.2	706000	5.85	3.94E+02
BF	6/23/2011	5.20E+00	15.3	1.05E+06	6.02	15.2	637333	5.8	3.94E+02
BF	6/23/2011	0.00E+00	15.2	1.02E+06	6.01	15.2	761333	5.88	3.94E+02
BF	6/23/2011	0.00E+00	16.7	1.15E+06	6.06	15.2	746667	5.87	3.94E+02
BF	6/23/2011	5.11E+00	14.8	1.17E+06	6.07	15.2	472500	5.67	3.94E+02
BF	7/6/2011	4.71E+00	64.7	1.33E+05	5.12	15.2	104000	5.02	1.33E+02
BF	7/6/2011	4.22E+00	54.8	1.17E+05	5.07	15.2	109333	5.04	1.33E+02
BF	7/6/2011	4.44E+00	52.1	1.61E+05	5.21	15.2	109833	5.04	1.33E+02
BF	7/6/2011	0.00E+00	56.1	1.38E+05	5.14	15.2	336167	5.53	1.33E+02
BF	7/6/2011	3.98E+00	55.7	1.35E+05	5.13	15.2	110833	5.04	1.33E+02
BF	7/6/2011	3.77E+00	48.7	1.26E+05	5.1	15.2	144167	5.16	1.33E+02
BF	7/6/2011	0.00E+00	40.4	1.23E+05	5.09	15.2	111000	5.05	1.33E+02
BF	7/6/2011	0.00E+00	41.6	1.19E+05	5.08	15.2	140500	5.15	1.33E+02
BF	7/6/2011	0.00E+00	36.3	1.35E+05	5.13	15.2	158667	5.2	1.33E+02
BF	7/6/2011	4.36E+00	19.1	1.23E+05	5.09	15.2	117500	5.07	1.33E+02

Table 6.1- Used for comparisons in SAS –Sand A

Sediment	Dates	Points	Depth (in)	Q (m^3/s)	Time (min)	Attachment (Fraction)	*E. coli* (cfu/100 mL) (Averaged for time periods)	*E. coli* Background In water per time period	Resuspension U ($cfu/m^2/s$)	Resuspension A ($cfu/m^2/s$)
Sand	7/13/2011	4.88	6.47	4.45E-03	0	0.16	5.12E+05	5.30E+05	0.00E+00	1.18E-06
Sand	7/13/2011	4.88	6.47	4.45E-03	15	0.34	5.12E+05	4.71E+05	0.00E+00	2.69E-06
Sand	7/13/2011	4.88	6.47	4.45E-03	30	0.05	5.12E+05	4.62E+05	0.00E+00	3.12E-07
Sand	7/13/2011	4.88	6.47	4.45E-03	45	0.07	5.12E+05	5.36E+05	0.00E+00	4.29E-07
Sand	7/13/2011	4.88	6.47	4.45E-03	60	0.13	5.12E+05	4.65E+05	0.00E+00	9.53E-07
Sand	7/13/2011	7.32	6.47	4.45E-03	0	0.24	3.71E+05	5.30E+05	0.00E+00	1.05E-06
Sand	7/13/2011	7.32	6.47	4.45E-03	15	0.1	3.71E+05	4.71E+05	1.95E-07	-4.22E-06
Sand	7/13/2011	7.32	6.47	4.45E-03	30	0.08	3.71E+05	4.62E+05	1.25E-07	5.34E-07
Sand	7/13/2011	7.32	6.47	4.45E-03	45	0.09	3.71E+05	5.36E+05	0.00E+00	1.95E-07
Sand	7/13/2011	7.32	6.47	4.45E-03	60	0.1	3.71E+05	4.65E+05	1.54E-06	-3.99E-07
Sand	7/22/2011	4.88	6.06	5.09E-03	0	0.12	5.42E+05	3.87E+05	0.00E+00	7.98E-07
Sand	7/22/2011	4.88	6.06	5.09E-03	15	0.01	5.42E+05	4.01E+05	1.14E-07	4.56E-08
Sand	7/22/2011	4.88	6.06	5.09E-03	30	0.08	5.42E+05	3.49E+05	2.85E-07	5.64E-07
Sand	7/22/2011	4.88	6.06	5.09E-03	45	0.28	5.42E+05	3.66E+05	0.00E+00	2.23E-06
Sand	7/22/2011	4.88	6.06	5.09E-03	60	0.05	5.42E+05	3.81E+05	0.00E+00	2.91E-07
Sand	7/22/2011	7.32	6.06	5.09E-03	0	0.39	5.77E+05	3.87E+05	0.00E+00	5.86E-06
Sand	7/22/2011	7.32	6.06	5.09E-03	15	0.22	5.77E+05	4.01E+05	0.00E+00	3.55E-06
Sand	7/22/2011	7.32	6.06	5.09E-03	30	0.11	5.77E+05	3.49E+05	0.00E+00	4.45E-07
Sand	7/22/2011	7.32	6.06	5.09E-03	45	0.03	5.77E+05	3.66E+05	1.47E-06	-4.12E-06
Sand	7/22/2011	7.32	6.06	5.09E-03	60	0.11	5.77E+05	3.81E+05	4.79E-07	9.69E-07
Sand	8/2/2011	4.88	6.06	1.04E-02	0	0	1.43E+06	1.14E+06	9.80E-06	-2.45E-06
Sand	8/2/2011	4.88	6.06	1.04E-02	15	0.05	1.43E+06	1.37E+06	0.00E+00	2.10E-06
Sand	8/2/2011	4.88	6.06	1.04E-02	30	0	1.43E+06	1.24E+06	2.87E-05	0.00E+00
Sand	8/2/2011	4.88	6.06	1.04E-02	45	0.07	1.43E+06	1.38E+06	0.00E+00	2.57E-06
Sand	8/2/2011	4.88	6.06	1.04E-02	60	0.26	1.43E+06	1.27E+06	1.17E-07	1.55E-05

Table 6.1										
Sand	8/2/2011	7.32	6.06	1.04E-02	0	0	1.39E+06	1.14E+06	1.04E-04	4.90E-06
Sand	8/2/2011	7.32	6.06	1.04E-02	15	0	1.39E+06	1.37E+06	9.01E-05	-4.20E-06
Sand	8/2/2011	7.32	6.06	1.04E-02	30	0.05	1.39E+06	1.24E+06	0.00E+00	4.27E-05
Sand	8/2/2011	7.32	6.06	1.04E-02	45	0.28	1.39E+06	1.38E+06	0.00E+00	1.96E-05
Sand	8/2/2011	7.32	6.06	1.04E-02	60	0.23	1.39E+06	1.27E+06	0.00E+00	-9.34E-06

Table 6.2 - Used for comparisons in SAS –Sand B

Sediment	Dates	Total Resuspension (cfu/m^2/s)	Turbidity (NTU)	LISST, Sizes (micro)	*E. coli* Sediment Before (cfu/100mL)	*E. coli* Sediment After (cfu/100mL)	Average Attached Composite Concentrations (cfu/100mL)
Sand	7/13/2011	1.18E-06	6.13	NA	6.77E+01	1.60E+08	7.90E+04
Sand	7/13/2011	2.69E-06	6.13	NA	6.77E+01	1.60E+08	1.80E+05
Sand	7/13/2011	3.12E-07	6.13	NA	6.77E+01	1.60E+08	2.08E+04
Sand	7/13/2011	4.29E-07	6.13	NA	6.77E+01	1.60E+08	2.87E+04
Sand	7/13/2011	9.53E-07	6.13	NA	6.77E+01	1.60E+08	6.37E+04
Sand	7/13/2011	1.05E-06	4.95	15.81	6.67E+01	1.60E+08	1.14E+05
Sand	7/13/2011	-4.02E-06	4.95	15.81	6.67E+01	1.60E+08	3.88E+04
Sand	7/13/2011	6.59E-07	4.95	15.81	6.67E+01	1.60E+08	3.87E+04
Sand	7/13/2011	1.95E-07	4.95	15.81	6.67E+01	1.60E+08	3.52E+04
Sand	7/13/2011	1.14E-06	4.95	15.81	6.67E+01	1.60E+08	5.03E+04
Sand	7/22/2011	7.98E-07	3.31	NA	0	6.64E+06	4.67E+04
Sand	7/22/2011	1.60E-07	3.31	NA	0	6.64E+06	2.67E+03
Sand	7/22/2011	8.49E-07	3.31	NA	0	6.64E+06	3.30E+04
Sand	7/22/2011	2.23E-06	3.31	NA	0	6.64E+06	1.30E+05
Sand	7/22/2011	2.91E-07	3.31	NA	0	6.64E+06	1.70E+04
Sand	7/22/2011	5.86E-06	3.38	11.02	0	6.64E+06	2.18E+05
Sand	7/22/2011	3.55E-06	3.38	11.02	0	6.64E+06	1.06E+05
Sand	7/22/2011	4.45E-07	3.38	11.02	0	6.64E+06	4.60E+04
Sand	7/22/2011	-2.64E-06	3.38	11.02	0	6.64E+06	1.00E+04
Sand	7/22/2011	1.45E-06	3.38	11.02	0	6.64E+06	4.53E+04
Sand	8/2/2011	7.35E-06	1.83	NA	5.69E+05	7.71E+06	0.00E+00
Sand	8/2/2011	2.10E-06	1.83	NA	5.69E+05	7.71E+06	6.00E+04
Sand	8/2/2011	2.87E-05	1.83	NA	5.69E+05	7.71E+06	0.00E+00
Sand	8/2/2011	2.57E-06	1.83	NA	5.69E+05	7.71E+06	7.33E+04
Sand	8/2/2011	1.56E-05	1.83	NA	5.69E+05	7.71E+06	4.43E+05

Table 6.2 Continued

Sand	8/2/2011	1.09E-04	2.00	24.98	5.69E+05	7.71E+06	0.00E+00
Sand	8/2/2011	8.59E-05	2.00	24.98	5.69E+05	7.71E+06	0.00E+00
Sand	8/2/2011	4.27E-05	2.00	24.98	5.69E+05	7.71E+06	6.33E+04
Sand	8/2/2011	1.96E-05	2.00	24.98	5.69E+05	7.71E+06	3.53E+05
Sand	8/2/2011	-9.34E-06	2.00	24.98	5.69E+05	7.71E+06	3.10E+05

Table 6.3 - Used for comparisons in SAS –Sand C

Sediment	Dates	Log (Average Attached Composites)	Turbidity per Time Composites	*E. coli* For each time (cfu/100 mL)	Log (*E. coli*)	Depth 2 (cm)	Average unattached Composite Concentrations (cfu/100ml)	Log(Average unattached)	H20 Background (cfu/100mL)
Sand	7/13/2011	4.90E+00	4.48	5.05E+05	5.7	15.2	412333	5.62	0.00E+00
Sand	7/13/2011	5.25E+00	4.9	5.33E+05	5.73	15.2	355000	5.55	0.00E+00
Sand	7/13/2011	4.32E+00	5.92	5.08E+05	5.71	15.2	422167	5.63	0.00E+00
Sand	7/13/2011	4.46E+00	4.26	5.14E+05	5.71	15.2	401833	5.6	0.00E+00
Sand	7/13/2011	4.80E+00	4.57	4.99E+05	5.7	15.2	419667	5.62	0.00E+00
Sand	7/13/2011	5.06E+00	4.75	3.93E+05	5.59	15.2	359333	5.56	0.00E+00
Sand	7/13/2011	4.59E+00	5.01	3.76E+05	5.57	15.2	361500	5.56	0.00E+00
Sand	7/13/2011	4.59E+00	4.32	3.77E+05	5.58	15.2	426333	5.63	0.00E+00
Sand	7/13/2011	4.55E+00	5.36	3.59E+05	5.55	15.2	368333	5.57	0.00E+00
Sand	7/13/2011	4.70E+00	3.73	3.53E+05	5.55	15.2	471000	5.67	0.00E+00
Sand	7/22/2011	4.67E+00	2.34	5.58E+05	5.75	15.2	352667	5.55	8.04E+03
Sand	7/22/2011	3.43E+00	4.4	5.61E+05	5.75	15.2	407667	5.61	8.04E+03
Sand	7/22/2011	4.52E+00	4.11	5.18E+05	5.71	15.2	365667	5.56	8.04E+03
Sand	7/22/2011	5.12E+00	3.95	4.91E+05	5.69	15.2	331000	5.52	8.04E+03
Sand	7/22/2011	4.23E+00	4.16	5.61E+05	5.75	15.2	357000	5.55	8.04E+03
Sand	7/22/2011	5.34E+00	3.8	5.49E+05	5.74	15.2	345333	5.54	8.04E+03
Sand	7/22/2011	5.03E+00	3.86	5.70E+05	5.76	15.2	381000	5.58	8.04E+03
Sand	7/22/2011	4.66E+00	4.28	5.58E+05	5.75	15.2	364000	5.56	8.04E+03
Sand	7/22/2011	4.00E+00	3.99	5.99E+05	5.78	15.2	374000	5.57	8.04E+03
Sand	7/22/2011	4.66E+00	4.26	5.76E+05	5.76	15.2	371000	5.57	8.04E+03
Sand	8/2/2011	0.00E+00	2.13	1.48E+06	6.17	15.2	1420000	6.15	1.37E+03
Sand	8/2/2011	4.78E+00	1.97	1.49E+06	6.17	15.2	1143333	6.06	1.37E+03
Sand	8/2/2011	0.00E+00	1.74	1.47E+06	6.17	15.2	2060000	6.31	1.37E+03
Sand	8/2/2011	4.87E+00	1.96	1.36E+06	6.13	15.2	930000	5.97	1.37E+03
Sand	8/2/2011	5.65E+00	2.28	1.35E+06	6.13	15.2	1273333	6.1	1.37E+03

Table 6.3 Continued

Sand	8/2/2011	0.00E+00	2.36	1.39E+06	6.14	15.2	2910000	6.46	1.37E+03
Sand	8/2/2011	0.00E+00	2.39	1.48E+06	6.17	15.2	2430000	6.39	1.37E+03
Sand	8/2/2011	4.80E+00	2.28	1.33E+06	6.12	15.2	1196667	6.08	1.37E+03
Sand	8/2/2011	5.55E+00	2.72	1.45E+06	6.16	15.2	896667	5.95	1.37E+03
Sand	8/2/2011	5.49E+00	2.29	1.37E+06	6.14	15.2	1013333	6.01	1.37E+03

Table 7.1 - Used for comparisons in SAS –Sand-Silt A

Sediment	Dates	Points	Depth (in)	Q (m^3/s)	Time (min)	Attachment (Fraction)	*E. coli* (Average) (cfu/100 mL)	*E. coli* Background In water per time period	Resuspension U ($cfu/m^2/s$)	Resuspension A ($cfu/m^2/s$)
SS	8/6/2011	4.88	6.09	1.56E-03	0	0.46	6.56E+05	5.27E+05	2.45E-07	2.60E-06
SS	8/6/2011	4.88	6.09	1.56E-03	15	0.29	6.56E+05	7.23E+05	5.24E-07	1.80E-06
SS	8/6/2011	4.88	6.09	1.56E-03	30	0.09	6.56E+05	3.50E+05	3.29E-06	5.07E-07
SS	8/6/2011	4.88	6.09	1.56E-03	45	0.27	6.56E+05	7.17E+05	1.40E-06	1.92E-06
SS	8/6/2011	4.88	6.09	1.56E-03	60	0.04	6.56E+05	1.14E+06	0.00E+00	2.45E-07
SS	8/6/2011	7.32	6.09	1.56E-03	0	0.22	6.13E+05	5.27E+05	4.54E-07	-3.43E-06
SS	8/6/2011	7.32	6.09	1.56E-03	15	0.34	6.13E+05	7.23E+05	0.00E+00	-5.24E-07
SS	8/6/2011	7.32	6.09	1.56E-03	30	0.06	6.13E+05	3.50E+05	0.00E+00	-4.54E-07
SS	8/6/2011	7.32	6.09	1.56E-03	45	0	6.13E+05	7.17E+05	0.00E+00	-7.97E-06
SS	8/6/2011	7.32	6.09	1.56E-03	60	0	6.13E+05	1.14E+06	0.00E+00	-1.12E-06
SS	8/23/2011	4.88	5.63	2.45E-03	0	0	3.63E+05	1.00E+04	2.74E-07	-1.37E-07
SS	8/23/2011	4.88	5.63	2.45E-03	15	0.46	3.63E+05	4.40E+05	0.00E+00	1.45E-06
SS	8/23/2011	4.88	5.63	2.45E-03	30	0.67	3.63E+05	4.53E+05	0.00E+00	2.44E-06
SS	8/23/2011	4.88	5.63	2.45E-03	45	0.37	3.63E+05	4.97E+05	0.00E+00	1.54E-06
SS	8/23/2011	4.88	5.63	2.45E-03	60	0.28	3.63E+05	4.57E+05	0.00E+00	1.29E-06
SS	8/23/2011	7.32	5.63	2.45E-03	0	0.33	3.96E+05	1.00E+04	3.84E-07	8.23E-07
SS	8/23/2011	7.32	5.63	2.45E-03	15	0.16	3.96E+05	4.40E+05	2.36E-06	-1.81E-06
SS	8/23/2011	7.32	5.63	2.45E-03	30	0.71	3.96E+05	4.53E+05	2.14E-06	6.20E-06
SS	8/23/2011	7.32	5.63	2.45E-03	45	0	3.96E+05	4.97E+05	1.15E-06	-3.18E-06
SS	8/23/2011	7.32	5.63	2.45E-03	60	0.22	3.96E+05	4.57E+05	0.00E+00	-1.15E-06
SS	9/1/2011	4.88	5.88	5.44E-03	0	0.23	8.27E+05	3.36E+05	3.18E-06	2.74E-06
SS	9/1/2011	4.88	5.88	5.44E-03	15	0.4	8.27E+05	3.23E+05	2.45E-06	5.61E-06
SS	9/1/2011	4.88	5.88	5.44E-03	30	0.4	8.27E+05	3.11E+05	3.65E-06	6.28E-06
SS	9/1/2011	4.88	5.88	5.44E-03	45	0.17	8.27E+05	3.24E+05	2.73E-06	1.83E-06
SS	9/1/2011	4.88	5.88	5.44E-03	60	0.15	8.27E+05	3.75E+05	2.66E-06	1.71E-06

Table 7.1 Continued

SS	9/1/2011	7.32	5.88	5.44E-03	0	0.24	7.46E+05	3.36E+05	0.00E+00	-1.22E-07
SS	9/1/2011	7.32	5.88	5.44E-03	15	0	7.46E+05	3.23E+05	2.20E-06	-1.24E-05
SS	9/1/2011	7.32	5.88	5.44E-03	30	0.23	7.46E+05	3.11E+05	0.00E+00	-8.05E-06
SS	9/1/2011	7.32	5.88	5.44E-03	45	0.13	7.46E+05	3.24E+05	1.83E-06	-8.54E-07
SS	9/1/2011	7.32	5.88	5.44E-03	60	0	7.46E+05	3.75E+05	4.88E-06	-8.54E-06

Table 7.2 - Used for comparisons in SAS –Sand-Silt B

Sediment	Dates	Log(Average Attached Composites)	Turbidity per Time Composites	*E. coli* For each time (cfu/100 mL)	Log (*E. coli*)	Depth 2 (cm)	Average unattached Composite Concentrations (cfu/100ml)	Log(Average unattached)
SS	8/6/2011	2.85E-06	2.63	0	0	1.50E+05	4.97E+05	5.70E+00
SS	8/6/2011	2.32E-06	2.63	0	0	1.50E+05	3.43E+05	5.54E+00
SS	8/6/2011	3.79E-06	2.63	0	0	1.50E+05	9.67E+04	4.99E+00
SS	8/6/2011	3.32E-06	2.63	0	0	1.50E+05	3.67E+05	5.56E+00
SS	8/6/2011	2.45E-07	2.63	0	0	1.50E+05	4.67E+04	4.67E+00
SS	8/6/2011	-2.97E-06	2.71	12.13	0	1.50E+05	1.70E+05	5.23E+00
SS	8/6/2011	-5.24E-07	2.71	12.13	0	1.50E+05	2.93E+05	5.47E+00
SS	8/6/2011	-4.54E-07	2.71	12.13	0	1.50E+05	5.33E+04	4.73E+00
SS	8/6/2011	-7.97E-06	2.71	12.13	0	1.50E+05	0.00E+00	0.00E+00
SS	8/6/2011	-1.12E-06	2.71	12.13	0	1.50E+05	0.00E+00	0.00E+00
SS	8/23/2011	1.37E-07	1.25	0	2.72E+07	1.76E+07	0.00E+00	0.00E+00
SS	8/23/2011	1.45E-06	1.25	0	2.72E+07	1.76E+07	1.77E+05	5.25E+00
SS	8/23/2011	2.44E-06	1.25	0	2.72E+07	1.76E+07	2.97E+05	5.47E+00
SS	8/23/2011	1.54E-06	1.25	0	2.72E+07	1.76E+07	1.87E+05	5.27E+00
SS	8/23/2011	1.29E-06	1.25	0	2.72E+07	1.76E+07	1.57E+05	5.19E+00
SS	8/23/2011	1.21E-06	1.06	14.64	2.72E+07	1.76E+07	3.33E+04	4.52E+00
SS	8/23/2011	5.48E-07	1.06	14.64	2.72E+07	1.76E+07	6.67E+04	4.82E+00
SS	8/23/2011	8.34E-06	1.06	14.64	2.72E+07	1.76E+07	6.73E+05	5.83E+00
SS	8/23/2011	-2.03E-06	1.06	14.64	2.72E+07	1.76E+07	0.00E+00	0.00E+00
SS	8/23/2011	-1.15E-06	1.06	14.64	2.72E+07	1.76E+07	8.67E+04	4.94E+00
SS	9/1/2011	5.93E-06	1.24	0	7.75E+06	1.60E+08	1.50E+05	5.18E+00
SS	9/1/2011	8.06E-06	1.24	0	7.75E+06	1.60E+08	3.07E+05	5.49E+00
SS	9/1/2011	9.92E-06	1.24	0	7.75E+06	1.60E+08	3.43E+05	5.54E+00
SS	9/1/2011	4.56E-06	1.24	0	7.75E+06	1.60E+08	1.00E+05	5.00E+00
SS	9/1/2011	4.36E-06	1.24	0	7.75E+06	1.60E+08	9.33E+04	4.97E+00

Table 7.2 Continued

SS	9/1/2011	-1.22E-07	3.62	37.24	7.75E+06	1.60E+08	1.47E+05	5.17E+00
SS	9/1/2011	-1.02E-05	3.62	37.24	7.75E+06	1.60E+08	0.00E+00	0.00E+00
SS	9/1/2011	-8.05E-06	3.62	37.24	7.75E+06	1.60E+08	1.23E+05	5.09E+00
SS	9/1/2011	9.76E-07	3.62	37.24	7.75E+06	1.60E+08	7.67E+04	4.88E+00
SS	9/1/2011	-3.66E-06	3.62	37.24	7.75E+06	1.60E+08	0.00E+00	0.00E+00

Table 7.3 - Used for comparisons in SAS –Sand-Silt C

Sediment	Dates	Turbidity per time Composites	*E. coli* (cfu/100 mL) For each time	Log of (*E. coli*)	Depth 2 (cm)	Average unattached Composite Concentrations cfu/100ml	Log (of Average unattached)	H20 Background cfu/100mL
SS	8/6/2011	1.62	4.87E+05	5.69	15.2	573333	5.76	4.73E+02
SS	8/6/2011	1.75	6.95E+05	5.84	15.2	823333	5.92	4.73E+02
SS	8/6/2011	1.65	6.48E+05	5.81	15.2	976667	5.99	4.73E+02
SS	8/6/2011	1.48	7.44E+05	5.87	15.2	983333	5.99	4.73E+02
SS	8/6/2011	1.48	6.84E+05	5.83	15.2	1090000	6.04	4.73E+02
SS	8/6/2011	2.15	4.60E+05	5.66	15.2	616667	5.79	4.73E+02
SS	8/6/2011	1.45	6.62E+05	5.82	15.2	570000	5.76	4.73E+02
SS	8/6/2011	1.51	5.89E+05	5.77	15.2	843333	5.93	4.73E+02
SS	8/6/2011	1.66	6.98E+05	5.84	15.2	943333	5.97	4.73E+02
SS	8/6/2011	1.82	6.91E+05	5.84	15.2	976667	5.99	4.73E+02
SS	8/23/2011	3.16	1.81E+04	4.26	15.2	43333	4.64	1.40E+02
SS	8/23/2011	3.16	4.21E+05	5.62	15.2	206667	5.32	1.40E+02
SS	8/23/2011	3.95	4.92E+05	5.69	15.2	146667	5.17	1.40E+02
SS	8/23/2011	4.13	4.08E+05	5.61	15.2	316667	5.5	1.40E+02
SS	8/23/2011	4.42	4.76E+05	5.68	15.2	403333	5.61	1.40E+02
SS	8/23/2011	2.25	4.09E+04	4.61	15.2	66667	4.82	1.40E+02
SS	8/23/2011	2.17	4.76E+05	5.68	15.2	350000	5.54	1.40E+02
SS	8/23/2011	2.62	4.62E+05	5.66	15.2	276667	5.44	1.40E+02
SS	8/23/2011	3.58	5.19E+05	5.71	15.2	386667	5.59	1.40E+02
SS	8/23/2011	3.65	4.83E+05	5.68	15.2	310000	5.49	1.40E+02
SS	9/1/2011	3.16	9.52E+05	5.98	15.2	510000	5.71	4.00E+00
SS	9/1/2011	3.16	7.42E+05	5.87	15.2	456667	5.66	4.00E+00
SS	9/1/2011	3.95	5.56E+05	5.75	15.2	510000	5.71	4.00E+00
SS	9/1/2011	4.13	4.06E+05	5.61	15.2	473333	5.68	4.00E+00
SS	9/1/2011	4.42	254508.7	5.41	15.2	520000	5.72	4.00E+00

Table 7.3 Continued

SS	9/1/2011	2.25	8.09E+05	5.91	15.2	453333	5.66	4.00E+00
SS	9/1/2011	2.17	8.64E+05	5.94	15.2	516667	5.71	4.00E+00
SS	9/1/2011	2.62	7.44E+05	5.87	15.2	420000	5.62	4.00E+00
SS	9/1/2011	3.58	6.20E+05	5.79	15.2	523333	5.72	4.00E+00
SS	9/1/2011	3.65	3.04E+05	5.48	15.2	653333	5.82	4.00E+00

Modeled and Calculated Resuspension Values

A-Table with Sediments at location 2 Physical Resuspension was calculated from the attached and unattached sediments. Resuspension U&A are averaged from the Physical Resuspension for the second segment. PU = Physical Resuspension Unattached, PA= Physical Resuspension Attached, RUA = Physical Resuspension Unattached Average, RAA= Physical Resuspension Attached Average, CMU= Calibrate Model without calibrated n Unattached, CMA = Calibrate Model without calibrated n attached, OMU = Original Model unattached, OMA = Original Model attached, CMUn = Calibrate Model without calibrated average n Unattached, CMAn == Calibrate Model without calibrated average n Attached, CMUn2 = Calibrate Model without calibrated n (for each bottom sediments) Unattached, and CMAn2 = Calibrate Model without calibrated n (for each bottom sediments) Attached.

Table 8.1 - Used for comparisons of Modeled and Calculated Resuspension Values

Sediment	PU	PA	RUA	RAA	CMU	CMA	OMU	OMA	CMUn	CMAn	CMUn2	CMAn2
BF	3.24E-06	-2.99E-05	1.78E-06	-8.06E-06	2.98E-09	1.09E-07	2.98E-12	5.81E+01	2.64E-07	2.20E-07	1.22E-06	-5.67E-06
BF	2.16E-06	-6.75E-06	1.78E-06	-8.06E-06	2.98E-09	1.09E-07	2.98E-12	5.81E+01	2.64E-07	2.20E-07	1.22E-06	-5.67E-06
BF	3.27E-09	-1.03E-05	1.78E-06	-8.06E-06	2.98E-09	1.09E-07	2.98E-12	5.81E+01	2.64E-07	2.20E-07	1.22E-06	-5.67E-06
BF	1.71E-06	1.47E-05	1.78E-06	-8.06E-06	2.98E-09	1.09E-07	2.98E-12	5.81E+01	2.64E-07	2.20E-07	1.22E-06	-5.67E-06
BF	1.34E-05	3.20E-06	1.34E-05	3.20E-06	1.15E-09	1.08E-08	1.15E-12	5.77E+00	9.02E-08	2.13E-08	1.57E-05	3.37E-06
Sand	3.71E-07	-5.67E-07	1.32E-05	3.84E-06	5.10E-08	9.47E-07	5.10E-11	5.57E+04	4.52E-06	2.32E-06	8.49E-06	3.95E-06
Sand	3.90E-07	1.34E-06	1.32E-05	3.84E-06	5.10E-08	9.47E-07	5.10E-11	5.57E+04	4.52E-06	2.32E-06	8.49E-06	3.95E-06
Sand	3.89E-05	1.07E-05	1.32E-05	3.84E-06	5.10E-08	9.47E-07	5.10E-11	5.57E+04	4.52E-06	2.32E-06	8.49E-06	3.95E-06
Sand	3.31E-07	3.72E-07	3.31E-07	3.72E-07	1.97E-07	3.95E-06	1.97E-10	2.33E+05	1.57E-05	9.49E-06	4.3E-07	4.04E-07
SS	9.09E-08	-2.70E-06	1.03E-06	-2.84E-06	3.30E-09	1.55E-04	3.30E-12	4.33E+03	2.93E-07	2.95E-04	1.35E-06	-2.17E-06
SS	1.21E-06	1.76E-07	1.03E-06	-2.84E-06	3.30E-09	1.55E-04	3.30E-12	4.33E+03	2.93E-07	2.95E-04	1.35E-06	-2.17E-06
SS	1.78E-06	-6.00E-06	1.03E-06	-2.84E-06	3.30E-09	1.55E-04	3.30E-12	4.33E+03	2.93E-07	2.95E-04	1.35E-06	-2.17E-06
SS	2.15E-06	6.84E-06	2.15E-06	6.84E-06	3.57E-07	6.22E-05	3.57E-10	1.74E+03	2.79E-05	1.15E-04	1.91E-06	7.07E-06

Appendix B Matlab Programs for processing data

ADV Analysis Program

Matlab program written by Dr. Rehmann originally for flume experiments. From output of ADV analyzes the velocity of the flume at multiple points and outputs error, average velocity and signal to noise ratios.

```
%  ADV_ANALYZE   Compute statistics of velocity measured with an ADV
%
%
%  Chris Rehmann, 11-5-09

%  Set the path

  codedir = pwd;
  addpath(codedir)

%  Clean up

  clear; close all

%  Set constants

  delimstr = ';';          %  Delimiter for the ADV files
  startrow = 10;           %  Starting row of data in ADV files
  startcol = 0;            %  Starting column of data in ADV files
  mincor   = 70;           %  Minimum correlation
  minSNR   = 5;            %  Minimum SNR
  alpha    = 0.01;         %  Convergence criterion for averaging

%  Find the filtered velocity files

  datadir = uigetdir;
  cd(datadir)
  dirstruct = dir('*.V?');     %  Get .Vf and .Vu files
  nfiles = length(dirstruct);
  [filename{1:nfiles}] = deal(dirstruct.name);

%  Process the files

  clc; disp([...
'Filename   Vx mean   Vy mean   Vz mean   % good    % spike    Tavgx (s)  Tavgy (s)  Tavgz (s)'])

  for ifile = 1:nfiles
      data = dlmread(filename{ifile},delimstr,startrow,startcol);
      %  Get the data
      ntotal = size(data,1);
```

```
    % Find the number of points

    cor0 = data(:,7);      SNR0 = data(:,10);
    % Get correlation and SNR
    cor1 = data(:,8);      SNR1 = data(:,11);
    cor2 = data(:,9);      SNR2 = data(:,12);

    spike_indx = find(cor0 == 0);
    % Spikes have blank data, or zeros
    nspikes    = length(spike_indx);
    % Number of spikes
    good_indx  = find(cor0 >= mincor & cor1 >= mincor & cor2 >= mincor & ...
                 SNR0 >= minSNR & SNR1 >= minSNR & SNR2 >= minSNR);
    ngood      = length(good_indx);
    % Number of good points

    Vx = data(good_indx,4);
    % Extract velocity components
    Vy = data(good_indx,5);
    Vz = data(good_indx,6);

    t = data(good_indx,1);
    Tavgx = avgtime(t,Vx,alpha);
    Tavgy = avgtime(t,Vy,alpha);
    Tavgz = avgtime(t,Vz,alpha);

    disp([filename{ifile} ' ' num2str(mean(Vx)) ' '...
       num2str(mean(Vy)) ' ' num2str(mean(Vz)) '    '...
        num2str(100*ngood/ntotal) '    ' num2str(100*nspikes/ntotal)...
        '  ' num2str(Tavgx) '  ' num2str(Tavgy)...
        '  ' num2str(Tavgz)])
end


%    Column       Variable
%      1        Time (seconds)
%      2        Position
%      3        Flag
%      4        x-velocity
%      5        y-velocity
%      6        z-velocity
%      7        Correlation 0
%      8        Correlation 1
%      9        Correlation 2
%     10        SNR 0
%     11        SNR 1
%     12        SNR 2
%     13        Amplitude 0
%     14        Amplitude 1
%     15        Amplitude 2
%     16        Average correlation
%     17        Average SNR
%     18        Average amplitude
```

Erosion Calculation and Resuspension Calculation

Matlab program written by Amy A Cervantes originally for resuspension experiments. From input of csv file read in and Erosion and Resuspension rates are calculated.

```
% Program to read in csv file for Amy A. Cervantes to double check her work
% Created Fall 2011, Modified through, Final edits 2/15/2012

% For this matlab code you must first have your data in an excel sheet and
% save as a csv file. Please note the output will be given in matrix form.
% A sample CSV file can be found in my Appendix for my thesis

beep off
clc
clear all
% Get to the correct filename and path
[filename,path,notimportant] = uigetfile();
% Put the path to file and filename together
fullpath = strcat(path, filename);

% Actually load the data. This creates a variable data with two arrays:
% data.data = array of data values based on csv file
% data.text = column titles and
data = importdata(fullpath);

%constants through, everything else changes and is in the CSV file
g = 9.81; % Gravity m/s^2
pi = 3.14;
a = 8.5E-16; % m^2 constante
b = 2.00E-2; % m^3/kg
ae = 8.5E-16; % m^2 constant, for unattached
be = 9.07E-3; % m^3/kg, for unattached
Eo = 1E-6; % assumed erosion rate at the threshold of erosion m/s AKA Eoa
Eoe = 1; % assumed erosion rate at the threshold of erosion m/s
S = 0.01; % percentage Slope in %
w = 0.6096; % meters width of flume
Pw = 1000; % Density of Water kg/m^3

% variables for looping over n's
dataoutrow = 1;
dataout_Res = cell(6,6);

% Now we do some CALCULATIONS!

% N/m^2 NONCOHESIVE Shear stress, where  d = is diameter in m, Tcn = d*414
Tcn = data.data(1:6,1)*414;

% C5 = Fb/d^2 Fb given in Figure 3.22 of Lick 2009 "Sediment and
% Contaminant Transport in Surface Water Introduction"
C5 = data.data(1:6,3)./(data.data(1:6,1).^2);

% C3 = (pi*(Pb-Pw)*g)/6; Pb = density of sediment, Pw = density of water
C3 = ((data.data(1:6,2)-Pw).*pi*g)./6;
```

```
% Equation for COHESIVE shear stress Tc =
% Tcn.*(1+(a.*exp(b.*Pb))./(d^2)+(C5./(C3.*d)));
Tc = Tcn.*(1+(a.*exp(b.*data.data(1:6,2)))./(data.data(1:6,1).^2)+(C5./...
   (C3.*data.data(1:6,1))));

% hydraulic radius based on height 6 inch and 9 inch heights (m).
% HR = (w*Height)./(w+2.*Height);
HR = (w*data.data(1:6,4))./(w+2.*data.data(1:6,4));

% Last shear stress is for regular stress based on slope only (N/m^2).
Tb = Pw*g*HR.*S;

% EROSION FINAL in m/s, E = Eo.*((Tb-Tcn)./(Tc-Tcn)).^n); Where n is a
% fitting parameter mostly assumed to be 2 but can be changed.
E = Eo.*((Tb-Tcn)./(Tc-Tcn)).^(data.data(1:6,7));

% Resuspension Calc ATTACHED Fractions % For right now we are assuming Eo
% is the same in both Equations no Eoa or Eoe yet UNITS cfu/m^2/s. This
% will be fitting issues. Ra = E.* Ca, where Ca is attached concentration
% in sediment. Ca [cfu/m^3)
Ra = E.*(data.data(1:6,5));

% Calculating what n should be for a perfect fit to the physical data
% measured. n = (Ra/ Ca.*Eo)))./(log((Tb-Tcn)./(Tc-Tcn)));
n = (log(data.data(1:6,12)./(data.data(1:6,5).*Eo)))./(log((Tb-Tcn)./...
   (Tc-Tcn)));


% Resuspension Calc UNattached Fractions
% N/m^2 NONCOHESIVE Shear stress, where d = is diameter in m, Tcn = d*414
Tcne = data.data(8:8,1)*414;

% C5 = Fb/d^2 Fb given in Figure 3.22 of Lick 2009 "Sediment and Contaminant
% Transport in Surface Water Introduction"
C5e = data.data(1:6,9)./(data.data(1:6,10).^2);

% C3 = (pi*(Pb-Pw)*g)/6; Pb = density of sediment, Pw = density of water
C3e = ((data.data(1:6,11)-Pw).*pi*g)./6;

% Equation for COHESIVE shear stress
% Tcne.*(1+(a.*exp(b.*Pb))./(d^2)+(C5./(C3.*d)));
Tce = Tcne.*(1+(ae.*exp(be.*data.data(1:6,11)))./(data.data(1:6,10).^2)+...
   (C5e./(C3e.*data.data(1:6,10))));

% hydraulic radius based on height 6 inch and 9 inch heights (m).
% HR = (w*Height)./(w+2.*Height);
HRe = (w*data.data(1:6,4))./(w+2.*data.data(1:6,4));

%Last shear stress is for regular stress based on slope only (N/m^2).
Tbe = Pw*g*HRe.*S;
```

```
% EROSION FINAL in m/s, E = Eo.*((Tb-Tcn)./(Tc-Tcn)).^nu); Where n is a
% fitting parameter mostly assumed to be 2 but can be changed.
Ee = Eoe.*((Tbe)./(Tce)).^(data.data(1:6,8));

% Resuspension Calc UNATTACHED Fractions % For right now we are assuming
% Eo is the same in both Equations no Eoa or Eoe yet UNITS cfu/m^2/s .
% This will be fitting issues. Ra = E.* Ca, where Ca is attached
% concentration in sedimente.  Ca [cfu/m^3)
Rae = Ee.*(data.data(1:6,6));

% Calculating what n should be for a perfect fit to the physical data
% measured. nu = (Ra/ Ca.*Eo))./(log((Tb-Tcn)./(Tc-Tcn)));
nu = (log(data.data(1:6,13)./(data.data(1:6,6).*Eoe)))./(log(Tbe./Tce));

% difference between calculate Resuspension and Physical model where
% data.data(1:6,12) and data.data(1:6,13)
DiffRa = Ra./data.data(1:6,12);
DiffRae = Rae./data.data(1:6,13);

 % Change the name of the file to reflect the variables used, output
 % includes all resuspension values
      for indx=1:length(Ra);
         dataoutrow = dataoutrow+1;
         dataout_Res(dataoutrow ,1:6) = num2cell([Ra(indx), n(indx),...
            DiffRa(indx), Rae(indx), nu(indx),DiffRae(indx)]);
      end
% Save data to csv file
csvwrite('NAME OF FILE.csv', cell2mat(dataout_Res));
% Change the name each time between 1.22 or 3.66
```

	Diameter (m)	Density (Kg/m^3)	Fb (N)	Depth (m)	Concentration of attachment (cfu/m^3)	Concentration of Unattachment (cfu/m^3)	n1	n2	Fb (N)	D (m)	Density (Kg/m^3)	Ra-Physical	Ru-Physical
SS	0.000044	1280	8.00E-09	0.158221	59083128	205.6667	7	2.1	1E-08	0.000001	1010	-2.84E-06	1.03E-06
SS11	0.000044	1280	8.00E-09	0.2413	14186700	13300	2	2.6	1E-08	0.000001	1010	6.84E-06	2.15E-06
Sand	0.0006	1520	7.50E-07	0.159808	57946863	3136.667	2	2.2	1E-08	0.000001	1010	3.84E-06	1.32E-05
Sand21	0.0006	1520	7.50E-07	0.22225	1.59E+08	8040	2	2.7	1E-08	0.000001	1010	3.72E-07	3.31E-07
Biofilm	0.000322	1400	2.50E-07	0.160393	132756.7	182.4444	-11	2.1	1E-08	0.000001	1010	-8.06E-06	1.78E-06
Biofilm31	0.000322	1400	2.50E-07	0.23495	8222.667	44	2	1.7	1E-08	0.000001	1010	3.20E-06	1.34E-05

Table 9.1 - Used for comparisons in Matlab CSV file

Example of CSV File for input of Sensitivity and Erosion-Resuspension calculations in Matlab.
Variables should be in order for Matlab code to work. Diameter (m), Density (kg/m^3), Fb (N), Depth (m), Concentration of *E. coli* in Sediment attached Ca (CFU/m^3), n1, n2, Fbe (N), De(m), Density (Kg/m^3), Resuspension attached physically calculated (CFU/m^2/s), and Resuspension unattached calculated (CFU/m^2/s).

LISST Output

Matlab program written by Amy A Cervantes originally for resuspension experiments. From input of LISST file read in and final particle size analysis as output.

```
%  LISST DATA Compute statistics of particle sizes
%
%
%  Amy Cervantes 09-23-11, reading LISST files into data files.

%  Set the path

   codedir = pwd;
   addpath(codedir)

%  Clean up

   clear; close all
   beep off

%  Set constants

   delimstr = ' ';            %  Delimiter for the LISST files
   startrow = 0;              %  Starting row of data in files
   startcol = 0;              %  Starting column of data in files
   stopcol = 32;              %  Starting column of data in files
   mcrnCnvFctr = 10^((log10(500)-log10(2.5))/32);

%  Find the filtered velocity files

   datadir = uigetdir;
   cd(datadir)
   dirstruct = dir('*.asc');                    %  Get .asc files
   nfiles = length(dirstruct);
   [filename{1:nfiles}] = deal(dirstruct.name);

%  Process the files

   clc; disp(['Filename                Microns '])% Load the sample data

%  Factors that multipy to the avearge to get the bin size multiplied.
 bins = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 0 0 0 0 0 0 0 0
0 0 0];
 MF = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0];
 %multiplication factor
for ifile = 1:nfiles
      data = dlmread(filename{ifile},delimstr,startrow,startcol);
      %  Get the data
      mu = mean(data);% Calculate the mean of each column
      Newarray = mu.*MF; % multiplying to get rid of last 10 bins
      TotalVolume = sum(Newarray); % gives the total of the averages
```

```
        T = Newarray.*bins; % multiply by the bins sizes
        TotalVbins = sum(T); % summing the bins*total Volumes
        Finalbins = TotalVbins/TotalVolume; %self explanatory but trying
        %to Figure out what bin size we should look at. TOTAL
        microns = 2.5*mcrnCnvFctr^(Finalbins); %Equation based on bins
        %being divided (Log (500)-log(2.5))/32
        disp([filename{ifile} ' ' num2str(microns)])
end
```

Flow Analysis

Matlab program written by Dr. Rehmann originally for flume experiments. From output of ADV ten point profile, analyzes the velocity of the flume at multiple points and outputs the flow rate in gpm.

```
%  QDRIVER   Process measurements to compute discharge
%
%
%  Chris Rehmann, 11-11-09

%  Clean up

  clear; close all

%  Set conversion factors

  in2cm = 2.54;              %  inches->cm
  cucms2gpm = 1.585e-2;      %  cm3/s -> gpm

%  Set constants

  H = [6 6.5]*in2cm;         %  Depth (cm)
  B = 60;                    %  Width (cm)

%  Load the data

%  data = load('C:\Chris\Research\Cowpie resuspension\aDV\Nov6\nov6stats.txt');
%  data = load('C:\Chris\Research\Cowpie resuspension\aDV\Nov19\nov19_stats.txt');
%  data = load('C:\Velocity Data\12-11 Report3.txt');

  [filename,pathname,dum] = uigetfile('*.txt','Get .txt file');
  data = load([pathname filename]);

  x   = data(:,2);                %  Downstream position (cm)
  y   = data(:,3);                %  Transverse position (cm)
  z   = data(:,4);                %  Vertical position (cm)
  vn1 = data(:,5);                %  Flow-normal component 1 (cm/s)
  vn2 = data(:,6);                %  Flow-normal component 2 (cm/s)
  u   = data(:,7);                %  Streamwise velocity (cm/s)

  U   = sqrt(vn1.^2 + vn2.^2 + u.^2);     %  Resultant velocity (cm/s)

%  Process the sets

  xs = unique(x);                 %  Find the downstream positions
  nx = length(xs);

  for i = 1:nx
```

```
    indx = find(x == xs(i));          %  Get the data at a cross-section
    yxs  = y(indx);
    zxs  = z(indx);
    uxs  = u(indx);
    Uxs  = U(indx);

    [Qlogx,Qlinx] = discharge(yxs,zxs,uxs,H(i),B);
    [Qlogr,Qlinr] = discharge(yxs,zxs,Uxs,H(i),B);
    disp(' ')
    disp(['Downstream position (cm):  ' num2str(xs(i))])
    disp(['Discharge with linear extrapolation and streamwise velocity (gpm):   '
num2str(Qlinx*cucms2gpm)])
    disp(['Discharge with log law fitting and streamwise velocity (gpm):       ' num2str(Qlogx*cucms2gpm)])
    disp(['Discharge with linear extrapolation and resultant velocity (gpm):    ' num2str(Qlinr*cucms2gpm)])
    disp(['Discharge with log law fitting and resultant velocity (gpm):        ' num2str(Qlogr*cucms2gpm)])
  end
```

Matlab program written by Amy A Cervantes originally for resuspension experiments. From input of csv file read in and sensitivity of a and b parameters as output.

```
% Program to read in csv file for Amy A. Cervantes to double check her work
% Created Fall 2011, Modified through, Final edits 2/15/2012

% For this matlab code you must first have your data in an excel sheet and
% save as a csv file. Please note the output will be given in matrix form.
% A sample CSV file can be found in my Appendix for my thesis


beep off
clc
clear all
% Get to the correct filename and path
[filename,path,notimportant] = uigetfile();
% Put the path to file and filename together
fullpath = strcat(path, filename);

% Actually load the data. This creates a variable data with two arrays:
% data.data = array of data values based on csv file
% data.text = column titles and
data = importdata(fullpath);

g = 9.81; %Gravity m/s^2
pi = 3.14;
ab = 8.5E-16; %m^2 constante
bb =  9.07E-3; % m^3/kg
Eo = 1E-6; % assumed erosion rate at the threshold of erosion m/s
Eoe = 1E-6; % assumed erosion rate at the threshold of erosion m/s
S = 0.01; % percentage Slope
w = 0.6096; % meters width of tank
Pw = 1000; % Density of Water kg/m^3
n1 = 2;
n2 = 2;

% variables for looping over a&b's, note we start at zero and go to values
% suggested, and delta = steps of difference for each iteration

amin=0; amax=1E-15; deltaa=1E-16;
bmin=0; bmax=1E-2; deltab=1E-3;
dataoutrow = 1;
dataout_a = cell(1+6*(((amax-amin)/deltaa)+1),11);
dataout_b = cell(1+6*(((bmax-bmin)/deltab)+1),11);

% for more details on the Calculations look at
% Calculations.Res.and.Erosion.using.CSV

% for loop over a
for a=amin:deltaa:amax;
  for b=bmin:deltab:bmax;
    % Now we do some CALCULATIONS!!
```

```
% N/m^2 NONCOHESIVE Shear stress
Tcn = data.data(1:6,1)*414;
% C5 = Fb/d^2 Fb given in Figure 3.22
C5 = data.data(1:6,3)./(data.data(1:6,1).^2);
% C3 = (pi*(Pb-Pw)*g)/6
C3 = ((data.data(1:6,2)-Pw).*pi*g)./6;
% Equation for COHESIVE shear stress
Tc = Tcn.*(1+(a.*exp(b.*data.data(1:6,2)))./(data.data(1:6,1).^2)+...
   (C5./(C3.*data.data(1:6,1))));
% hydraulic radius based on height the .1's are the 9 inch heights (m).
HR = (w*data.data(1:6,4))./(w+2.*data.data(1:6,4));
% Last shear stress is for regular stress based on slope only (N/m^2).
Tb = Pw*g*HR.*S;
% EROSION FINAL in m/s
E = Eo.*((Tb-Tcn)./(Tc-Tcn)).^(n1);
% Resuspension Calc ATTACHED Fractions % For right now we are assuming Eo
% is the same in both Equations no Eoa or Eou yet. This will be fitting
% issues.
Ra = E.*(data.data(1:6,5));

% for loop over b
% Resuspension Calc UNattached Fractions
Tcne = data.data(8:8,1)*414;
C5e = data.data(1:6,9)./(data.data(1:6,10).^2);
% C3 = (pi*(Pb-Pw)*g)/6
C3e = ((data.data(1:6,11)-Pw).*pi*g)./6;
% Equation for COHESIVE shear stress
Tce = Tcne.*(1+(a.*exp(b.*data.data(1:6,11)))./...
   (data.data(1:6,10).^2)+(C5e./(C3e.*data.data(1:6,10))));
% hydraulic radius based on height the .1's are the 9 inch heights (m).
HRe = (w*data.data(1:6,4))./(w+2.*data.data(1:6,4));
% Last shear stress is for regular stress based on slope only (N/m^2).
Tbe = Pw*g*HRe.*S;
% EROSION FINAL in m/s
Ee = Eoe.*((Tbe)./(Tce)).^(n2);
% Resuspension Calc UNATTACHED Fractions % For right now we are assuming Eo is
% the same in both Equations no Eoa or Eou yet. This will be fitting issues.
Rae = Ee.*(data.data(1:6,6));
% nu =
%      (log(data.data(1:6,13)./(data.data(1:6,6).*Eoe)))./(log(Tbe./Tce));

% Sensitivity Calcs: S =
% Abs((R-Rphysically).*ab)./((a-ab)*(Rphysically)), where ab = bas
% value, a = value iteration
Saa = abs((Ra-data.data(1:6,12)).*ab)./((a-ab).*data.data(1:6,12));
Saae = abs((Rae-data.data(1:6,13)).*ab)./((a-ab).*data.data(1:6,13));
Sab = abs((Ra-data.data(1:6,12)).*bb)./((b-bb).*data.data(1:6,12));
Saeb = abs((Rae-data.data(1:6,13)).*bb)./((b-bb).*data.data(1:6,13));

% Change the name of the file to reflect the variables used
for indx=1:length(Ra);
   dataoutrow = dataoutrow+1;
   dataout_a(dataoutrow ,1:11) = num2cell([data.data(indx,1),...
      data.data(indx,2),data.data(indx,3), data.data(indx,4),...
```

```
        data.data(indx,5),data.data(indx,6),a, Ra(indx), Rae(indx),...
        Saa(indx), Saae(indx)]);
      dataout_b(dataoutrow ,1:11) = num2cell([data.data(indx,1),...
        data.data(indx,2),data.data(indx,3), data.data(indx,4),...
        data.data(indx,5),data.data(indx,6), b, Ra(indx), Rae(indx),...
        Sab(indx), Saeb(indx)]);
   end
  end
end

% Save data to csv file
csvwrite('Sensitivity_a_b_a.csv', cell2mat(dataout_a));
csvwrite('Sensitivity_a_b_b.csv', cell2mat(dataout_b));
```

Sensitivity Analysis

Matlab program written by Amy A Cervantes originally for resuspension experiments. From input of csv file read in and sensitivity of Eo and Eoe parameters as output.

```
% Program to read in csv file for Amy A. Cervantes to double check her work
% Created Fall 2011, Modified through, Final edits 2/15/2012

% For this matlab code you must first have your data in an excel sheet and
% save as a csv file. Please note the output will be given in matrix form.
% A sample CSV file can be found in my Appendix for my thesis


beep off
clc
clear all
% Get to the correct filename and path
[filename,path,notimportant] = uigetfile();
% Put the path to file and filename together
fullpath = strcat(path, filename);

% Actually load the data. This creates a variable data with two arrays:
% data.data = array of data values based on csv file
% data.text = column titles and
data = importdata(fullpath);

g = 9.81; % Gravity m/s^2
pi = 3.14;
a = 8.5E-16; % m^2 constante
b =  9.07E-3; % m^3/kg
Eob = 1E-6; % assumed erosion rate at the threshold of erosion m/s
Eoeb = 1E-6; % assumed erosion rate at the threshold of erosion m/s
S = 0.01; % percentage Slope
w = 0.6096; % meters width of tank
Pw = 1000; % Density of Water kg/m^3
n1 = 2;
n2 = 2;

% variables for looping over Eo's, note we start at zero and go to values
% suggested, and delta = steps of difference for each iteration
Eomin=1E-6; Eomax=1; deltaEo=1;
Eoemin=1E-6; Eoemax=1; deltaEoe=1;
dataoutrow = 1;
% calculation for figuring out how large the excel output should be
dataout_Eo = cell(1+6*(((log10(Eomax)-log10(Eomin))/deltaEo)+1)*...
   (((log10(Eoemax)-log10(Eoemin))/deltaEoe)+1),10);
dataout_Eoe = cell(1+6*(((log10(Eomax)-log10(Eomin))/deltaEo)+1)*...
   (((log10(Eoemax)-log10(Eoemin))/deltaEoe)+1),10);

% for more details on the Calculations look at
% Calculations.Res.and.Erosion.using.CSV
```

```
% for loop over Eo
for Eoindx=log10(Eomin):deltaEo:log10(Eomax);
   Eo = 10^(Eoindx);
   % Now we do some CALCULATIONS!!!!!!!!
   % N/m^2 NONCOHESIVE Shear stress
   Tcn = data.data(1:6,1)*414;
   % C5 = Fb/d^2 Fb given in Figure 3.22
   C5 = data.data(1:6,3)./(data.data(1:6,1).^2);
   % C3 = (pi*(Pb-Pw)*g)/6
   C3 = ((data.data(1:6,2)-Pw).*pi*g)./6;
   % Equation for COHESIVE shear stress
   Tc = Tcn.*(1+(a.*exp(b.*data.data(1:6,2)))./(data.data(1:6,1).^2)+...
      (C5./(C3.*data.data(1:6,1))));
   % hydraulic radius based on height the .1's are the 9 inch heights (m).
   HR = (w*data.data(1:6,4))./(w+2.*data.data(1:6,4));
   % Last shear stress is for regular stress based on slope only (N/m^2).
   Tb = Pw*g*HR.*S;
   % EROSION FINAL in m/s
   E = Eo.*((Tb-Tcn)./(Tc-Tcn)).^(n1);
   % Resuspension Calc ATTACHED Fractions % For right now we are assuming Eo is
   % the same in both Equations no Eoa or Eou yet. This will be fitting issues.
   Ra = E.*(data.data(1:6,5));


   % for loop over Eoe
   for Eoeindx=log10(Eoemin):deltaEoe:log10(Eoemax);
      Eoe = 10^(Eoeindx);
      % Resuspension Calc UNattached Fractions
      Tcne = data.data(8:8,1)*414;
      C5e = data.data(1:6,9)./(data.data(1:6,10).^2);
      % C3 = (pi*(Pb-Pw)*g)/6
      C3e = ((data.data(1:6,11)-Pw).*pi*g)./6;
      % Equation for COHESIVE shear stress
      Tce = Tcne.*(1+(a.*exp(b.*data.data(1:6,11)))./...
         (data.data(1:6,10).^2)+(C5e./(C3e.*data.data(1:6,10))));
      % hydraulic radius based on height the .1's are the 9 inch heights (m).
      HRe = (w*data.data(1:6,4))./(w+2.*data.data(1:6,4));
      % Last shear stress is for regular stress based on slope only (N/m^2).
      Tbe = Pw*g*HRe.*S;
      % EROSION FINAL in m/s
      Ee = Eoe.*((Tbe)./(Tce)).^(n2);
      % Resuspension Calc UNATTACHED Fractions % For right now we are
      % assuming Eo isthe same in both Equations no Eoa or Eou yet.
      Rae = Ee.*(data.data(1:6,6));

      % Sensitivity Calcs: S =
      % Abs((Ra-Rphysically).*Eob)./((Eo-Eob)*(Rphysically)), where Eob
      % and Eoeb = bas value, Eo/oe = value iteration
      Sa = abs((Ra-data.data(1:6,12)).*Eob)./((Eo-Eob)...
         .*data.data(1:6,12));
      Sb = abs((Rae-data.data(1:6,13)).*Eoeb)./((Eoe-Eoeb)...
```

```
        .*data.data(1:6,13));

    % Change the name of the file to reflect the variables used
    for indx=1:length(Ra);
      dataoutrow = dataoutrow+1;
      dataout_Eo(dataoutrow ,1:10) = num2cell([data.data(indx,1),...
        data.data(indx,2),data.data(indx,3), data.data(indx,4),...
        data.data(indx,5),data.data(indx,6), Eo, Ra(indx), ...
        Rae(indx), Sa(indx)]);
      dataout_Eoe(dataoutrow ,1:10) = num2cell([data.data(indx,1),...
        data.data(indx,2),data.data(indx,3), data.data(indx,4),...
        data.data(indx,5),data.data(indx,6), Eoe, Ra(indx), ...
        Rae(indx), Sb(indx)]);
    end
  end
end

% Save data to csv file

csvwrite('Sensitivity_Eo_Eoe_Eo.csv', cell2mat(dataout_Eo));
csvwrite('Sensitivity_Eo_Eoe_Eoe.csv', cell2mat(dataout_Eoe));
```

Matlab program written by Amy A Cervantes originally for resuspension experiments. From input of csv file read in and sensitivity of n1 and n2 parameters as output.

```
% Program to read in csv file for Amy A. Cervantes to double check her work
% Created Fall 2011, Modified through, Final edits 2/15/2012

% For this matlab code you must first have your data in an excel sheet and
% save as a csv file. Please note the output will be given in matrix form.
% A sample CSV file can be found in my Appendix for my thesis


beep off
clc
clear all
% Get to the correct filename and path
[filename,path,notimportant] = uigetfile();
% Put the path to file and filename together
fullpath = strcat(path, filename);

% Actually load the data. This creates a variable data with two arrays:
% data.data = array of data values based on csv file
% data.text = column titles and
data = importdata(fullpath);

g = 9.81; % Gravity m/s^2
pi = 3.14;
a = 8.5E-16; % m^2 constante
b =  9.07E-3; % m^3/kg
Eo = 1E-6; % assumed erosion rate at the threshold of erosion m/s
Eoe = 1E-6; % assumed erosion rate at the threshold of erosion m/s
S = 0.01; % percentage Slope
w = 0.6096; % meters width of tank
Pw = 1000; % Density of Water kg/m^3
n1b = 2.0;
n2b = 2.0;

% variables for looping over n's
n1min=1; n1max=5; deltan1=0.1;
n2min=0; n2max=5; deltan2=0.1;
dataoutrow = 1;
% calculation for figuring out how large the excel output should be
dataout_n1 = cell(1+6*(((n1max-n1min)/deltan1)+1)*...
   (((n2max-n2min)/deltan2)+1),10);
dataout_n2 = cell(1+6*(((n1max-n1min)/deltan1)+1)*...
   (((n2max-n2min)/deltan2)+1),10);

% for more details on the Calculations look at
% Calculations.Res.and.Erosion.using.CSV

% for loop over n1
for n1=n1min:deltan1:n1max;
   % Now we do some CALCULATIONS!!!!!!!!
   % N/m^2 NONCOHESIVE Shear stress
   Tcn = data.data(1:6,1)*414;
```

```
% C5 = Fb/d^2 Fb given in Figure 3.22
C5 = data.data(1:6,3)./(data.data(1:6,1).^2);
% C3 = (pi*(Pb-Pw)*g)/6
C3 = ((data.data(1:6,2)-Pw).*pi*g)./6;
% Equation for COHESIVE shear stress
Tc = Tcn.*(1+(a.*exp(b.*data.data(1:6,2)))./(data.data(1:6,1).^2)...
   +(C5./(C3.*data.data(1:6,1))));
% hydraulic radius based on height the .1's are the 9 inch heights (m).
HR = (w*data.data(1:6,4))./(w+2.*data.data(1:6,4));
% Last shear stress is for regular stress based on slope only (N/m^2).
Tb = Pw*g*HR.*S;
% EROSION FINAL in m/s
E = Eo.*((Tb-Tcn)./(Tc-Tcn)).^(n1);
% Resuspension Calc ATTACHED Fractions % For right now we are assuming Eo is
% the same in both Equations no Eoa or Eou yet. This will be fitting issues.
Ra = E.*(data.data(1:6,5));



% for loop over n2
for n2=n2min:deltan2:n2max;
   % Resuspension Calc UNattached Fractions
   Tcne = data.data(8:8,1)*414;
   C5e = data.data(1:6,9)./(data.data(1:6,10).^2);
   % C3 = (pi*(Pb-Pw)*g)/6
   C3e = ((data.data(1:6,11)-Pw).*pi*g)./6;
   % Equation for COHESIVE shear stress
   Tce = Tcne.*(1+(a.*exp(b.*data.data(1:6,11)))./...
      (data.data(1:6,10).^2)+(C5e./(C3e.*data.data(1:6,10))));
   % hydraulic radius based on height the .1's are the 9 inch heights(m).
   HRe = (w*data.data(1:6,4))./(w+2.*data.data(1:6,4));
   % Last shear stress is for regular stress based on slope only (N/m^2).
   Tbe = Pw*g*HRe.*S;
   % EROSION FINAL in m/s
   Ee = Eoe.*((Tbe)./(Tce)).^(n2);
   % Resuspension Calc UNATTACHED Fractions % For right now we are
   % assuming Eo isthe same in both Equations no Eoa or Eou yet.
   Rae = Ee.*(data.data(1:6,6));

   % Sensitivity Calcs: S =
   % Abs((Ra-Rphysically).*n1b)./((n1-n1b)*(Rphysically)), where n1b
   % and n2b = bas value, n1/2 = value iteration
   Sa = abs((Ra-data.data(1:6,12)).*n1b)./((n1-n1b).*data.data(1:6,12));
   Sb = abs((Rae-data.data(1:6,13)).*n2b)./((n2-n2b).*data.data(1:6,13));

   % Change the name of the file to reflect the variables used
   for indx=1:length(Ra);
      dataoutrow = dataoutrow+1;
      dataout_n1(dataoutrow ,1:10) = num2cell([data.data(indx,1),...
         data.data(indx,2),data.data(indx,3), data.data(indx,4),...
         data.data(indx,5),data.data(indx,6),n1,Ra(indx), ...
         Rae(indx), Sa(indx)]);
      dataout_n2(dataoutrow ,1:10) = num2cell([data.data(indx,1),...
         data.data(indx,2),data.data(indx,3),data.data(indx,4),...
         data.data(indx,5),data.data(indx,6),n2, Ra(indx), ...
```

```
            Rae(indx), Sb(indx)]);
        end
    end
end

% Save data to csv file

csvwrite('Sensitivity_n1.csv', cell2mat(dataout_n1));
csvwrite('Sensitivity_n2.csv', cell2mat(dataout_n2));
```

Appendix C SAS Code and Output

SAS program written by Amy Cervantes originally for Resuspension Experiments. Written for the comparison of biofilm and flow rates using the input data sheet from Appendix A.

```
data sheet;
input Sediment $ HighMedLow$ Dates $ Points Depth Q Time Attachment EColi EColiBackground
ResuspensionU ResuspensionA TotalResuspension Turbidity LISSTSizes EColiSedBefore
EColiSedimentAfter AA LogAA TurbidityT Concentration LogC Height2 AU LogAU WaterBackground Q2;
cards;
;
run;

proc print data = sheet;
run;

proc sort data = sheet;
by sediment;
run;

proc corr data = sheet;
by sediment;
var LISSTSizes TurbidityT Q Attachment ResuspensionU ResuspensionA Concentration Ecoli Points;
title 'Correlation ';
run;
proc glm data = sheet;
class HighMedLow sediment;
model LISSTSizes = HighMedLow Sediment sediment*HighMedLow;
lsmeans HighMedLow Sediment sediment*HighMedLow/ ADJUST=Tukey pdiff;
title 'LISSTSizes Vs. HighMedLow and sediment';
run;
proc glm data = sheet;
class HighMedLow sediment;
model TurbidityT = HighMedLow Sediment sediment*HighMedLow;
lsmeans HighMedLow Sediment sediment*HighMedLow/ ADJUST=Tukey pdiff;
title 'Turbidity Vs. HighMedLow and sediment';
run;
proc glm data = sheet;
class HighMedLow sediment;
model Attachment = HighMedLow Sediment sediment*HighMedLow;
```

```
lsmeans HighMedLow Sediment sediment*HighMedLow/ ADJUST=Tukey pdiff;
title 'Attachment Vs. HighMedLow and sediment';
run;
proc glm data = sheet;
class EColiSedimentAfter sediment;
model WaterBackground = EColiSedimentAfter sediment;
lsmeans EColiSedimentAfter/ ADJUST=Tukey pdiff;
title 'E. coli Sediment After Vs. WaterBackground';
run;
proc glm data = sheet;
class AA sediment;
model TurbidityT = AA sediment;
lsmeans sediment/ ADJUST=Tukey pdiff;
title 'AA Vs. TurbidityT';
run;

options formdlim=' ';
ods pdf startpage=no;
```

SAS program written by Amy Cervantes originally for Resuspension Experiments. Written for the comparison of biofilm and flow resuspension rates using the input data sheet from Appendix A.

```
data sheet;
input Sediment $ HighMedLow$ Dates $     Points    Depth    Q          Time     Attachment        EColi     EColiBackground
ResuspensionU    ResuspensionA    TotalResuspension          Turbidity          LISSTSizes        EColiSedBefore
EColiSedimentAfter          AA        LogAA  TurbidityT          Concentration      LogC     Height2 AU LogAU          WaterBackground Q2 ;
cards;
;
run;

proc print data = sheet;
run;

proc sort data = sheet;
by Sediment;

run;

proc glm data = sheet;
class HighMedLow sediment;
model TotalResuspension = HighMedLow Sediment sediment*HighMedLow;
lsmeans HighMedLow Sediment sediment*HighMedLow/ ADJUST=Tukey pdiff;
title 'Total Resuspension Vs. HighMedLow and sediment';
run;
proc glm data = sheet;
class HighMedLow sediment;
model ResuspensionA = HighMedLow Sediment sediment*HighMedLow;
lsmeans HighMedLow Sediment sediment*HighMedLow/ ADJUST=Tukey pdiff;
title 'ResuspensionA Vs. HighMedLow and sediment';
run;
proc glm data = sheet;
class HighMedLow sediment;
model ResuspensionU = HighMedLow Sediment sediment*HighMedLow;
lsmeans HighMedLow Sediment sediment*HighMedLow/ ADJUST=Tukey pdiff;
title 'ResuspensionU Vs. HighMedLow and sediment';
run;
proc glm data = sheet;
```

```
class sediment;
model TotalResuspension = Turbidity Sediment ;
lsmeans sediment/ ADJUST=Tukey pdiff;
title 'Turbidity Vs.  sediment';
run;
proc glm data = sheet;
class sediment;
model TotalResuspension = EColi Sediment ;
lsmeans sediment/ ADJUST=Tukey pdiff;
title 'Concentrations Vs.  sediment';
run;
proc glm data = sheet;
class sediment;
model TotalResuspension = EColiSedimentAfter Sediment ;
lsmeans sediment/ ADJUST=Tukey pdiff;
title 'Sediment Concentrations Vs. sediment';
run;
options formdlim=' ';
ods pdf startpage=no;
```

SAS program written by Amy Cervantes originally for Resuspension Experiments. Written for the comparison time comparison on different sediments. Data sheet can be found in Appendix A.

```
data sheet;
input Sediment $ Dates $ Points Depth Q Time Attachment EColi EColiBackground
ResuspensionU ResuspensionA TotalResuspension Turbidity LISSTSizes EColiSedBefore
EColiSedimentAfter AA LogAA TurbidityT Concentration LogC Height2 AU LogAU WaterBackground;
cards;
;
run;

proc print data = sheet;
run;

proc sort data = sheet;
by dates;
run;
proc glm data = sheet;
by dates;
class time;
model LogAA = time;
lsmeans time / ADJUST=Tukey pdiff;
title 'LogAA vs Time';
run;
*I'm trying something new, Reuspension Unattached;
proc glm data = sheet;
by dates;
class time;
model LogAU = time;
lsmeans time / ADJUST=Tukey pdiff;
title 'Log UA vs Time';
run;
*I'm trying something new, ReuspensionTOTAL Unattached;
proc glm data = sheet;
by dates;
class time;
model TotalResuspension = time;
lsmeans time / ADJUST=Tukey pdiff;
title 'Total Resuspension vs Time';
```

```
run;
proc glm data = sheet;
by dates;
class time;
model ResuspensionU = time;
lsmeans time / ADJUST=Tukey pdiff;
title 'ResuspensionU vs Time';
run;
proc glm data = sheet;
by dates;
class time;
model ResuspensionA = time;
lsmeans time / ADJUST=Tukey pdiff;
title 'ResuspensionA vs Time';
run;

options formdlim=' ';
ods pdf startpage=no;
```

SAS program written by Amy Cervantes originally for Resuspension Experiments. Written for the comparison of 15 cm depth and 23 cm with different sediments and heights Data sheet can be found in Appendix A.

```
 data sheet;
input Sediment $ HighMedLow$ Dates $ Points Depth Q Time Attachment EColi EColiBackground
ResuspensionU ResuspensionA TotalResuspension Turbidity LISSTSizes EColiSedBefore
EColiSedimentAfter AA LogAA TurbidityT Concentration LogC Height2 AU LogAU WaterBackground Q2 ;
cards;
;
run;

proc print data = sheet;
run;

proc sort data = sheet;
by Sediment;

run;

proc corr data = sheet;
by Sediment;
var Q TurbidityT height2 Attachment ResuspensionU ResuspensionA Concentration Ecoli LISSTSizes;
title 'Correlation';
run;
proc glm data = sheet;
class height2 sediment;
model LISSTSizes = height2 Sediment sediment*height2;
lsmeans height2 Sediment sediment*height2/ ADJUST=Tukey pdiff;
title 'LISSTSizes Vs. height2 and sediment';
run;
proc glm data = sheet;
class height2 sediment;
model TurbidityT = height2 Sediment sediment*height2;
lsmeans height2 Sediment sediment*height2/ ADJUST=Tukey pdiff;
title 'Turbidity Vs. height2 and sediment';
run;
proc glm data = sheet;
class height2 sediment;
model Attachment = height2 Sediment sediment*height2;
```

```
lsmeans height2 Sediment sediment*height2/ ADJUST=Tukey pdiff;
title 'Attachment Vs. height2 and sediment';
run;

options formdlim=' ';
ods pdf startpage=no;
```

SAS program written by Amy Cervantes originally for Resuspension Experiments. Written for the comparison of 15 cm depth and 23 cm with different sediments and heights for Resuspension only Data sheet can be found in Appendix A.

```
data sheet;
input Sediment $ HighMediumLow$ Dates $ Points Depth Q Time Attachment EColi EColiBackground
ResuspensionU ResuspensionA TotalResuspension Turbidity LISSTSizes EColiSedBefore
EColiSedimentAfter AA LogAA TurbidityT Concentration LogC Height2 AU LogAU WaterBackground Q2 ;
cards;
;
run;

proc print data = sheet;
run;

proc sort data = sheet;
by Sediment;

run;

proc glm data = sheet;
class height2 sediment;
model TotalResuspension = height2 Sediment sediment*height2;
lsmeans height2 Sediment sediment*height2/ ADJUST=Tukey pdiff;
title 'Total Resuspension Vs. height2 and sediment';
run;
proc glm data = sheet;
class height2 sediment;
model ResuspensionU = height2 Sediment sediment*height2;
lsmeans height2 Sediment sediment*height2/ ADJUST=Tukey pdiff;
title 'ResuspensionU Vs. height2 and sediment';
run;
proc glm data = sheet;
class height2 sediment;
model ResuspensionA = height2 Sediment sediment*height2;
lsmeans height2 Sediment sediment*height2/ ADJUST=Tukey pdiff;
title 'Total ResuspensionA Vs. height2 and sediment';
run;

options formdlim=' ';
```

```
ods pdf startpage=no;
```

SAS program written by Amy Cervantes originally for Resuspension Experiments. Written for the comparison of model comparisons with different sediments and heights for Resuspension only Data sheet can be found in Appendix A.

```
data sheet;
input Sediment$ PU PA RUA RAA CMU CMA OMU OMA CMUn CMAn CMUn2 CMAn2;
cards;
BF 3.24E-06 -2.99E-05 1.78E-06 -8.06E-06 2.98E-09 1.09E-07 2.98E-12 5.81E+01 2.64E-
07 2.20E-07 0.00000122 -5.67E-06
BF 2.16E-06 -6.75E-06 1.78E-06 -8.06E-06 2.98E-09 1.09E-07 2.98E-12 5.81E+01 2.64E-
07 2.20E-07 0.00000122 -5.67E-06
BF 3.27E-09 -1.03E-05 1.78E-06 -8.06E-06 2.98E-09 1.09E-07 2.98E-12 5.81E+01 2.64E-
07 2.20E-07 0.00000122 -5.67E-06
BF 1.71E-06 1.47E-05 1.78E-06 -8.06E-06 2.98E-09 1.09E-07 2.98E-12 5.81E+01 2.64E-
07 2.20E-07 0.00000122 -5.67E-06
BF 1.34E-05 3.20E-06 1.34E-05 3.20E-06 1.15E-09 1.08E-08 1.15E-12 5.77E+00 9.02E-
08 2.13E-08 0.00001574 3.37E-06
Sand 3.71E-07 -5.67E-07 1.32E-05 3.84E-06 5.10E-08 9.47E-07 5.10E-11 5.57E+04 4.52E-
06 2.32E-06 0.00000849 3.95E-06
Sand 3.90E-07 1.34E-06 1.32E-05 3.84E-06 5.10E-08 9.47E-07 5.10E-11 5.57E+04 4.52E-
06 2.32E-06 0.00000849 3.95E-06
Sand 3.89E-05 1.07E-05 1.32E-05 3.84E-06 5.10E-08 9.47E-07 5.10E-11 5.57E+04 4.52E-
06 2.32E-06 0.00000849 3.95E-06
Sand 3.31E-07 3.72E-07 3.31E-07 3.72E-07 1.97E-07 3.95E-06 1.97E-10 2.33E+05 1.57E-
05 9.49E-06 0.00000043 4.04E-07
SS 9.09E-08 -2.70E-06 1.03E-06 -2.84E-06 3.30E-09 1.55E-04 3.30E-12 4.33E+03 2.93E-
07 2.95E-04 0.00000135 -2.17E-06
SS 1.21E-06 1.76E-07 1.03E-06 -2.84E-06 3.30E-09 1.55E-04 3.30E-12 4.33E+03 2.93E-
07 2.95E-04 0.00000135 -2.17E-06
SS 1.78E-06 -6.00E-06 1.03E-06 -2.84E-06 3.30E-09 1.55E-04 3.30E-12 4.33E+03 2.93E-
07 2.95E-04 0.00000135 -2.17E-06
SS 2.15E-06 6.84E-06 2.15E-06 6.84E-06 3.57E-07 6.22E-05 3.57E-10 1.74E+03 2.79E-
05 1.15E-04 0.00000191 7.07E-06
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Correlation Tables for Similar Depths

Table 10.1 – Correlation Tables for 15 cm Water Height

6 inches-Sand	LISSTSizes	Turbidity	Q	Attachment	Resuspension U	Resuspension A	Concentration	EColi	Points
LISSTSizes	1	-0.14446	0.27383	0.04372	0.40648	0.2459	0.22088	0.21349	0.90355
		0.4463	0.1431	0.8186	0.0258	0.1902	0.2408	0.2573	0.0001
TurbidityT	-0.14446	1	-0.88369	0.15769	-0.36315	-0.2687	-0.87416	-0.87859	0.06423
	0.4463		0.0001	0.4053	0.0486	0.1511	0.0001	0.0001	0.736
Q	0.27383	-0.88369	1	-0.18316	0.44191	0.33907	0.99178	0.99486	0
	0.1431	0.0001		0.3326	0.0145	0.0668	0.0001	0.0001	1
Attachment	0.04372	0.15769	-0.18316	1	-0.36824	0.15244	-0.19664	-0.17344	0.11508
	0.8186	0.4053	0.3326		0.0453	0.4213	0.2977	0.3594	0.5448
ResuspensionU	0.40648	-0.36315	0.44191	-0.36824	1	-0.08534	0.45318	0.42897	0.2163
	0.0258	0.0486	0.0145	0.0453		0.6539	0.0119	0.018	0.251
ResuspensionA	0.2459	-0.2687	0.33907	0.15244	-0.08534	1	0.30388	0.3367	0.1117
	0.1902	0.1511	0.0668	0.4213	0.6539		0.1026	0.0689	0.5568
Concentration	0.22088	-0.87416	0.99178	-0.19664	0.45318	0.30388	1	0.99639	-0.05069
	0.2408	0.0001	0.0001	0.2977	0.0119	0.1026		0.0001	0.7902
EColi	0.21349	-0.87859	0.99486	-0.17344	0.42897	0.3367	0.99639	1	-0.05612
	0.2573	0.0001	0.0001	0.3594	0.018	0.0689	0.0001		0.7684
Points	0.90355	0.06423	0	0.11508	0.2163	0.1117	-0.05069	-0.05612	1
	0.0001	0.736	1	0.5448	0.251	0.5568	0.7902	0.7684	
Sand-SILT	**LISSTSizes**	**Turbidity**	**Q**	**Attachment**	**Resuspension U**	**Resuspension A**	**Concentration**	**EColi**	**Points**
LISSTSizes	1	-0.09654	0.42019	-0.31046	0.0785	-0.68557	0.18974	0.19086	0.80054
		0.6118	0.0208	0.095	0.6801	0.0001	0.3153	0.3124	0.0001
TurbidityT	-0.09654	1	0.53209	0.17611	0.28928	0.20174	-0.38377	-0.09302	-0.28541
	0.6118		0.0025	0.3519	0.121	0.285	0.0363	0.6249	0.1263
Q	0.42019	0.53209	1	-0.06216	0.57912	-0.10523	0.14751	0.62121	0

	0.0208	0.0025		0.7442	0.0008	0.58	0.4366	0.0002	1
Attachment	-0.31046	0.17611	-0.06216	1	-0.11676	0.64044	-0.07526	-0.2535	-0.29421
	0.095	0.3519	0.7442		0.5389	0.0001	0.6927	0.1765	0.1145
ResuspensionU	0.0785	0.28928	0.57912	-0.11676	1	0.04119	0.02228	0.51145	-0.11971
	0.6801	0.121	0.0008	0.5389		0.8289	0.907	0.0039	0.5286
ResuspensionA	-0.68557	0.20174	-0.10523	0.64044	0.04119	1	-0.1432	-0.08237	-0.59006
	0.0001	0.285	0.58	0.0001	0.8289		0.4503	0.6652	0.0006
Concentration	0.18974	-0.38377	0.14751	-0.07526	0.02228	-0.1432	1	0.49568	0.06924
	0.3153	0.0363	0.4366	0.6927	0.907	0.4503		0.0053	0.7162
EColi	0.19086	-0.09302	0.62121	-0.2535	0.51145	-0.08237	0.49568	1	-0.08908
	0.3124	0.6249	0.0002	0.1765	0.0039	0.6652	0.0053		0.6397
Points	0.80054	-0.28541	0	-0.29421	-0.11971	-0.59006	0.06924	-0.08908	1
	0.0001	0.1263	1	0.1145	0.5286	0.0006	0.7162	0.6397	

BF	**LISSTSizes**	**Turbidity**	**Q**	**Attachment**	**Resuspension U**	**Resuspension A**	**Concentration**	**EColi**	**Points**
LISSTSizes	1	-0.29492	-0.32549	-0.19489	0.08592	-0.7161	0.40017	0.38376	0.87655
		0.0647	0.0404	0.2282	0.5981	0.0001	0.0105	0.0145	0.0001
TurbidityT	-0.29492	1	0.76315	-0.41174	0.10108	0.14981	-0.50621	-0.51994	-0.11309
	0.0647		0.0001	0.0083	0.5349	0.3562	0.0009	0.0006	0.4872
Q	-0.32549	0.76315	1	-0.08238	-0.03148	0.28723	-0.76532	-0.79929	0
	0.0404	0.0001		0.6133	0.8471	0.0723	0.0001	0.0001	1
Attachment	-0.19489	-0.41174	-0.08238	1	-0.34682	0.179	0.08716	0.08786	-0.30825
	0.2282	0.0083	0.6133		0.0283	0.2691	0.5928	0.5898	0.053
ResuspensionU	0.08592	0.10108	-0.03148	-0.34682	1	-0.43039	-0.09727	-0.05981	0.05623
	0.5981	0.5349	0.8471	0.0283		0.0056	0.5504	0.7139	0.7304
ResuspensionA	-0.7161	0.14981	0.28723	0.179	-0.43039	1	-0.34425	-0.34608	-0.46658
	0.0001	0.3562	0.0723	0.2691	0.0056		0.0296	0.0287	0.0024
Concentration	0.40017	-0.50621	-0.76532	0.08716	-0.09727	-0.34425	1	0.98441	0.13747
	0.0105	0.0009	0.0001	0.5928	0.5504	0.0296		0.0001	0.3976

EColi	0.38376	-0.51994	-0.79929	0.08786	-0.05981	-0.34608	0.98441	1	0.1127
	0.0145	0.0006	0.0001	0.5898	0.7139	0.0287	0.0001		0.4887
Points	0.87655	-0.11309	0	-0.30825	0.05623	-0.46658	0.13747	0.1127	1
	0.0001	0.4872	1	0.053	0.7304	0.0024	0.3976	0.4887	

Correlation Tables for Different Depths

Table 11.1 – Correlation Tables for 15 cm and 23 Water Height comparison

SAND	Q	Turbidity T	Height2	Attachment	Resuspension U	ResuspensionA	Concentration	EColi	LISSTSizes
Q	1	-0.91563	1	-0.50318	-0.02041	-0.02815	-0.63534	-0.64385	0.24435
		0.0001	0.0001	0.0237	0.9319	0.9062	0.0026	0.0022	0.2991
TurbidityT	-0.91563	1	-0.91563	0.48951	-0.12694	0.00738	0.63781	0.63105	-0.35724
	0.0001		0.0001	0.0285	0.5938	0.9754	0.0025	0.0028	0.122
Height2	1	-0.91563	1	-0.50318	-0.02041	-0.02815	-0.63534	-0.64385	0.24435
	0.0001	0.0001		0.0237	0.9319	0.9062	0.0026	0.0022	0.2991
Attachment	-0.50318	0.48951	-0.50318	1	-0.1681	0.51783	0.41723	0.40307	-0.29371
	0.0237	0.0285	0.0237		0.4787	0.0194	0.0672	0.078	0.2088
ResuspensionU	-0.02041	-0.12694	-0.02041	-0.1681	1	-0.17465	-0.26269	-0.18807	0.33516
	0.9319	0.5938	0.9319	0.4787		0.4614	0.2632	0.4272	0.1486
ResuspensionA	-0.02815	0.00738	-0.02815	0.51783	-0.17465	1	0.34142	0.36596	-0.1503
	0.9062	0.9754	0.9062	0.0194	0.4614		0.1407	0.1125	0.5271
Concentration	-0.63534	0.63781	-0.63534	0.41723	-0.26269	0.34142	1	0.95157	-0.50712
	0.0026	0.0025	0.0026	0.0672	0.2632	0.1407		0.0001	0.0225
EColi	-0.64385	0.63105	-0.64385	0.40307	-0.18807	0.36596	0.95157	1	-0.50064
	0.0022	0.0028	0.0022	0.078	0.4272	0.1125	0.0001		0.0246
LISSTSizes	0.24435	-0.35724	0.24435	-0.29371	0.33516	-0.1503	-0.50712	-0.50064	1
	0.2991	0.122	0.2991	0.2088	0.1486	0.5271	0.0225	0.0246	
Sand-SILT	**Q**	**Turbidity T**	**Height2**	**Attachment**	**Resuspension U**	**ResuspensionA**	**Concentration**	**EColi**	**LISSTSizes**
Q	1	0.87649	1	0.23587	0.36116	0.26578	0.87667	0.8927	-0.26839
		0.0001	0.0001	0.3168	0.1177	0.2574	0.0001	0.0001	0.2526
TurbidityT	0.87649	1	0.87649	0.10169	0.42184	0.15096	0.76395	0.74649	-0.34361
	0.0001		0.0001	0.6697	0.0639	0.5252	0.0001	0.0002	0.138
Height2	1	0.87649	1	0.23587	0.36116	0.26578	0.87667	0.8927	-0.26839

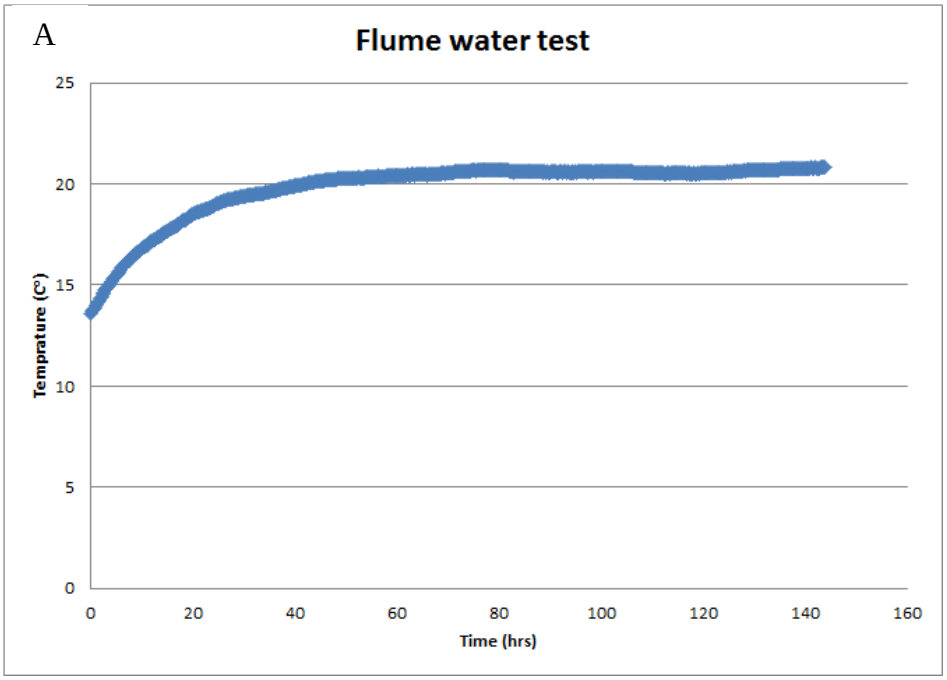
	0.0001	0.0001		0.3168	0.1177	0.2574	0.0001	0.0001	0.2526
Attachment	0.23587	0.10169	0.23587	1	-0.36479	0.68302	0.26153	0.24282	-0.12107
	0.3168	0.6697	0.3168		0.1138	0.0009	0.2654	0.3023	0.6111
ResuspensionU	0.36116	0.42184	0.36116	-0.36479	1	-0.29238	0.29253	0.27852	-0.01341
	0.1177	0.0639	0.1177	0.1138		0.211	0.2107	0.2344	0.9553
ResuspensionA	0.26578	0.15096	0.26578	0.68302	-0.29238	1	0.22897	0.19618	-0.13589
	0.2574	0.5252	0.2574	0.0009	0.211		0.3315	0.4071	0.5678
Concentration	0.87667	0.76395	0.87667	0.26153	0.29253	0.22897	1	0.98203	-0.01963
	0.0001	0.0001	0.0001	0.2654	0.2107	0.3315		0.0001	0.9345
EColi	0.8927	0.74649	0.8927	0.24282	0.27852	0.19618	0.98203	1	-0.02001
	0.0001	0.0002	0.0001	0.3023	0.2344	0.4071	0.0001		0.9333
LISSTSizes	-0.26839	-0.34361	-0.26839	-0.12107	-0.01341	-0.13589	-0.01963	-0.02001	1
	0.2526	0.138	0.2526	0.6111	0.9553	0.5678	0.9345	0.9333	

BF	**Q**	**Turbidity T**	**Height2**	**Attachment**	**Resuspension U**	**ResuspensionA**	**Concentration**	**EColi**	**LISSTSizes**
Q	1	-0.96203	-1	0.71967	-0.40969	-0.26664	0.12026	0.69966	0.32461
		0.0001	0.0001	0.0003	0.0728	0.2558	0.6135	0.0006	0.1626
TurbidityT	-0.96203	1	0.96203	-0.73048	0.43318	0.20283	0.00087	-0.58244	-0.19317
	0.0001		0.0001	0.0003	0.0564	0.3911	0.9971	0.007	0.4145
Height2	-1	0.96203	1	-0.71967	0.40969	0.26664	-0.12026	-0.69966	-0.32461
	0.0001	0.0001		0.0003	0.0728	0.2558	0.6135	0.0006	0.1626
Attachment	0.71967	-0.73048	-0.71967	1	-0.51307	0.14628	-0.11575	0.42174	0.12779
	0.0003	0.0003	0.0003		0.0207	0.5383	0.627	0.064	0.5913
ResuspensionU	-0.40969	0.43318	0.40969	-0.51307	1	-0.20219	0.04688	-0.22856	-0.05327
	0.0728	0.0564	0.0728	0.0207		0.3926	0.8444	0.3324	0.8235
ResuspensionA	-0.26664	0.20283	0.26664	0.14628	-0.20219	1	-0.44109	-0.56726	-0.58734
	0.2558	0.3911	0.2558	0.5383	0.3926		0.0516	0.0091	0.0065
Concentration	0.12026	0.00087	-0.12026	-0.11575	0.04688	-0.44109	1	0.68858	0.84062
	0.6135	0.9971	0.6135	0.627	0.8444	0.0516		0.0008	0.0001

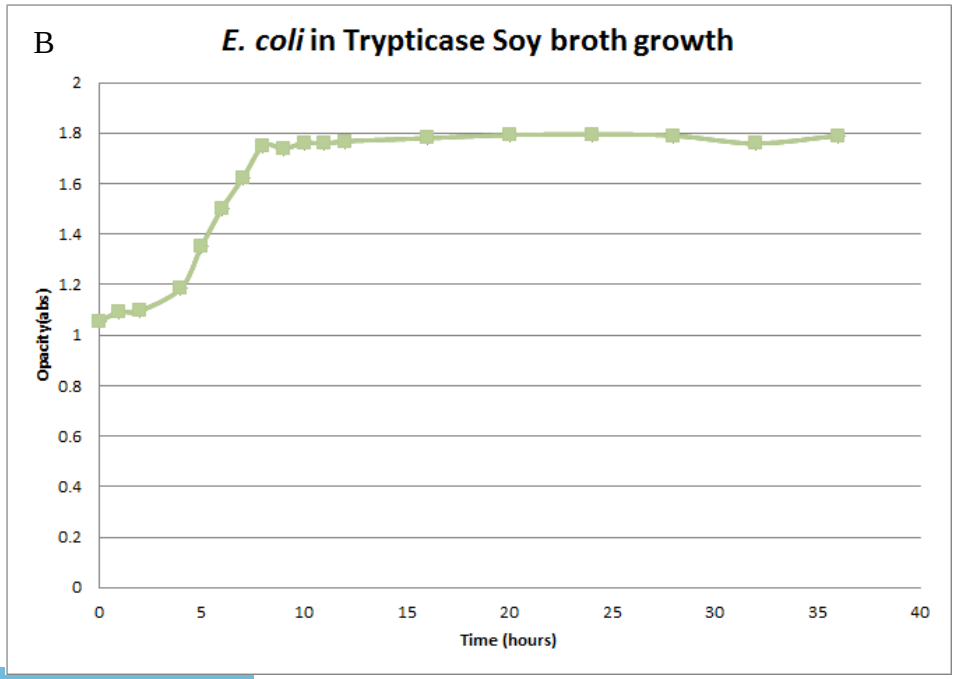
EColi	0.69966	-0.58244	-0.69966	0.42174	-0.22856	-0.56726	0.68858	1	0.90281
	0.0006	0.007	0.0006	0.064	0.3324	0.0091	0.0008		0.0001
LISSTSizes	0.32461	-0.19317	-0.32461	0.12779	-0.05327	-0.58734	0.84062	0.90281	1
	0.1626	0.4145	0.1626	0.5913	0.8235	0.0065	0.0001	0.0001	

Appendix D Graphs & Bright Field Microscopy

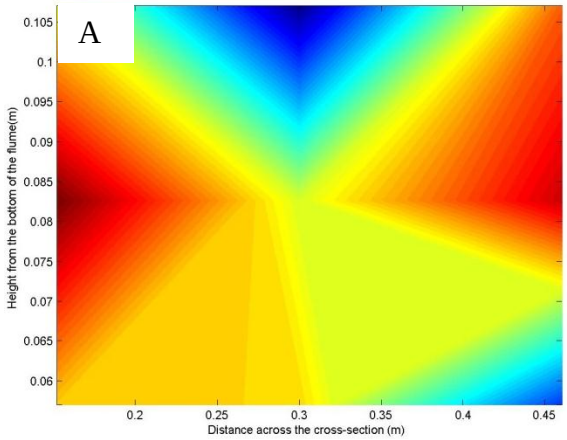
Water Temperature Tests and *E. coli* Growth in TSB

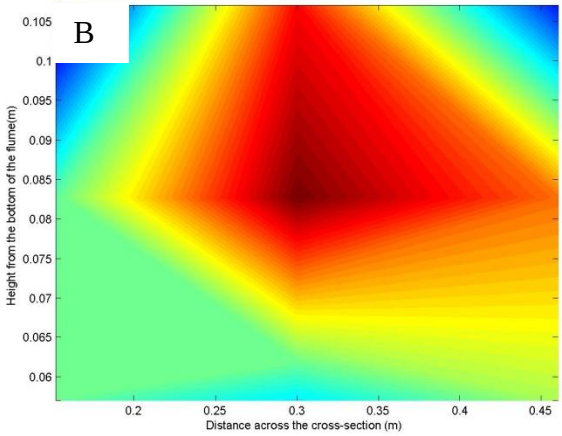


A- Flume water Temperature test vs time for combination of two small pumps, 200 and 300 gpm. Used to determine maximum length of time before water temperature plateau
B- *E. coli* in TSB measured over time to maximize growth time in water bath at 44.5C^{o}. Minimum time was 10 hours and maximum time was 14 hours for the experiments

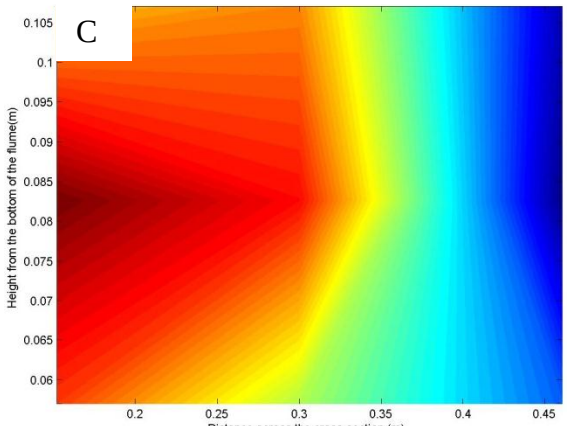


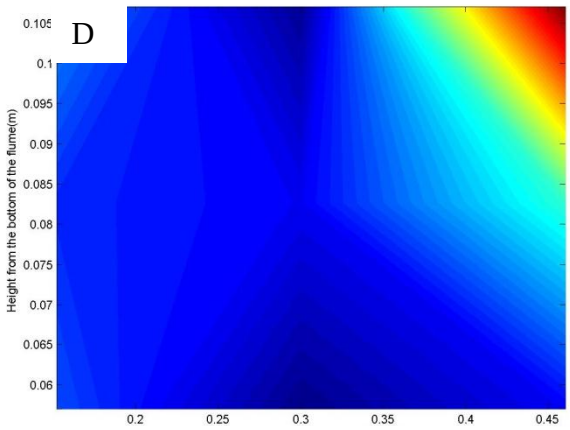
Bacterial Concentrations Over Flume Cross Sections



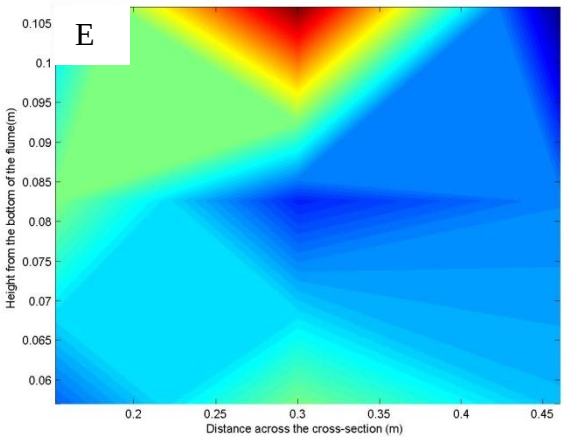


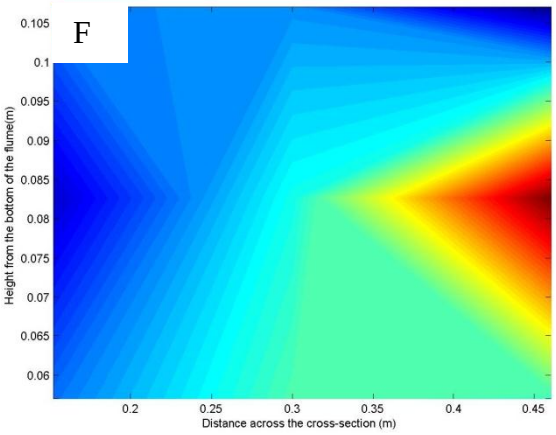
A-Biofilm Concentration Diagram for location 1 at Q =1.26E-2
B-Biofilm Concentration Diagram for location 2 at Q =1.26E-2
C-Biofilm Concentration Diagram for location 2 at Q =1.42E-2

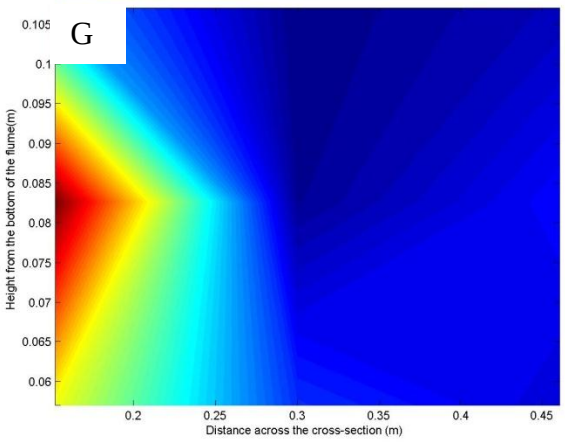


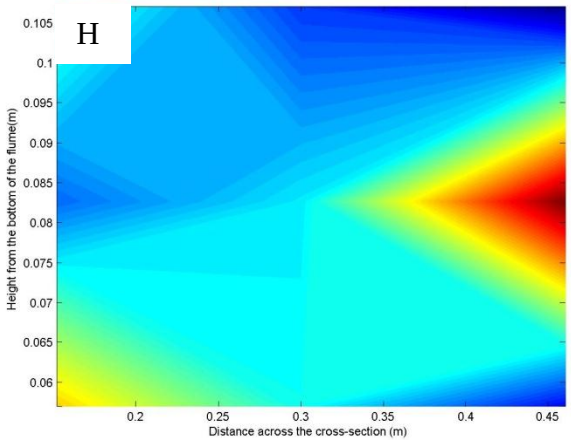


D-Biofilm Concentration Diagram for location 2at Q =1.42E-2
E-Biofilm Concentration Diagram for location 1 at Q =1.45E-2
F-Biofilm Concentration Diagram for location 2 at Q = 1.45E-2

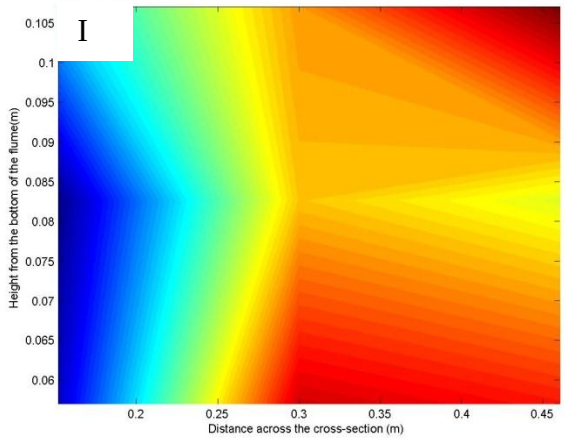


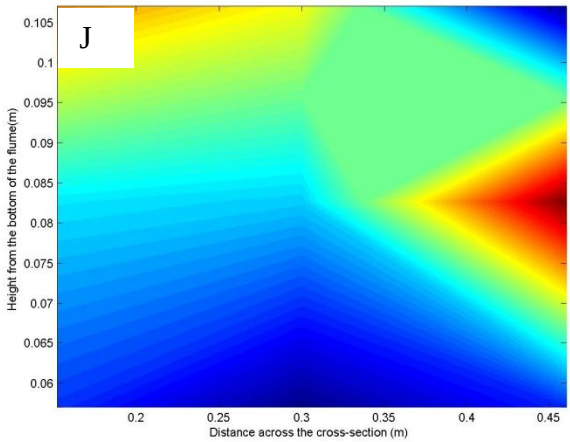


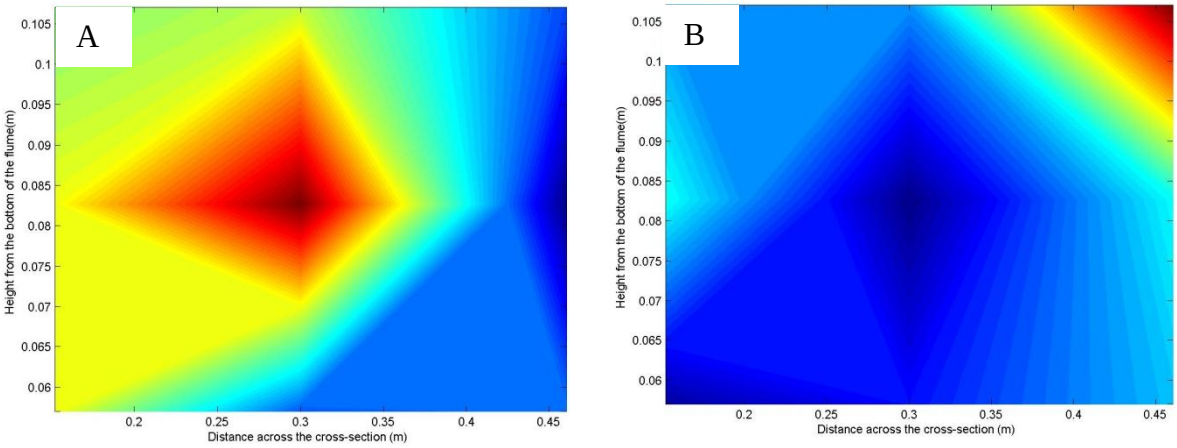




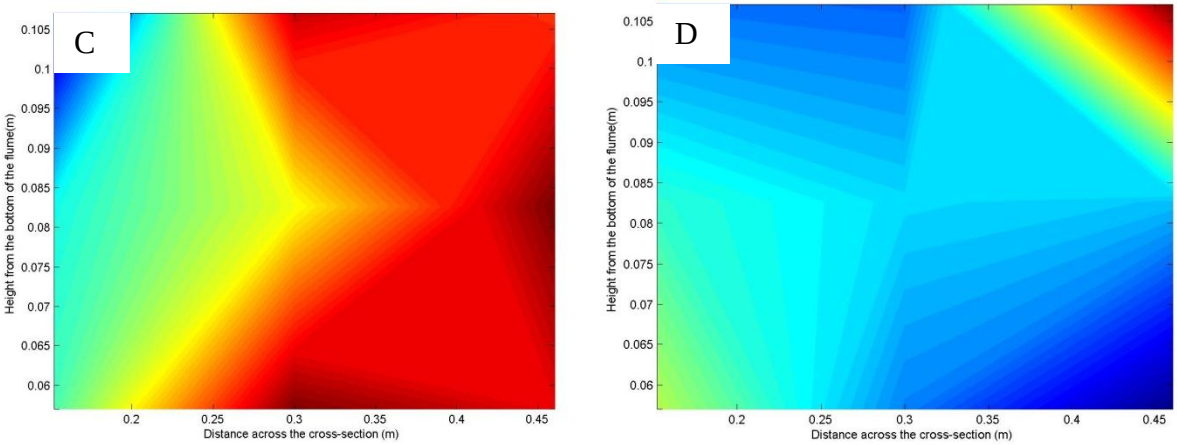
G-Biofilm Concentration Diagram for location 1 at Q =1.46E-2
H-Biofilm Concentration Diagram for location 2 at Q =1.46E-2
I-Biofilm Concentration Diagram for location 1 at Q = 1.61E-2
J-Biofilm Concentration Diagram for location 2 at Q = 1.61E-2



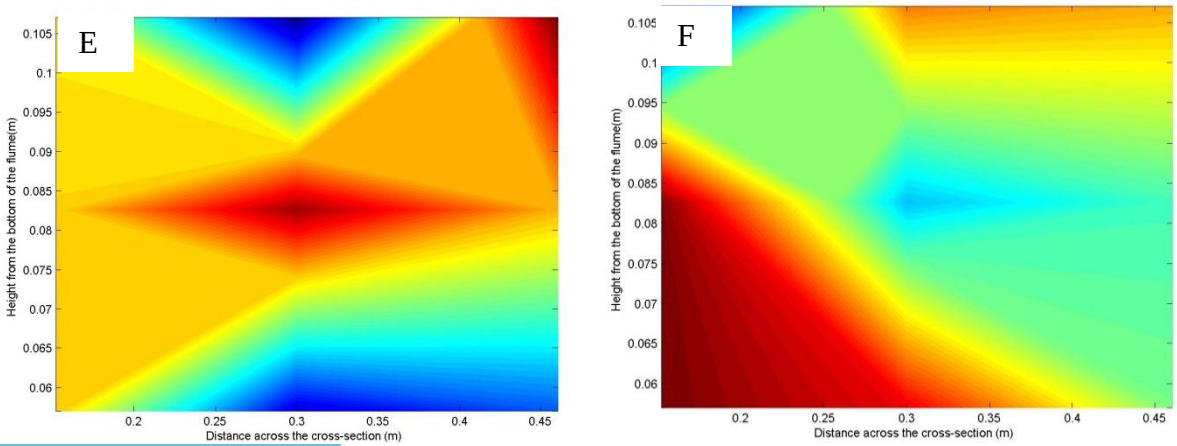


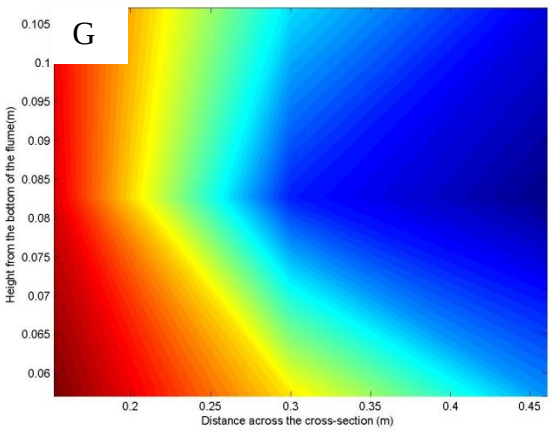


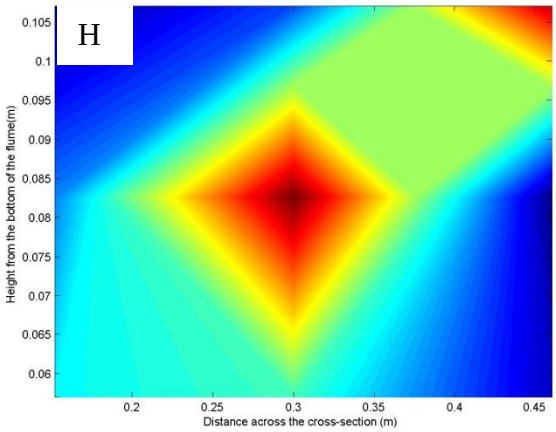
A-Sand Concentration Diagram for location 1 at Q =1.04E-2
B-Sand Concentration Diagram for location 2 at Q =1.04E-2
C-Sand Concentration Diagram for location 1 at Q =4.45E-3



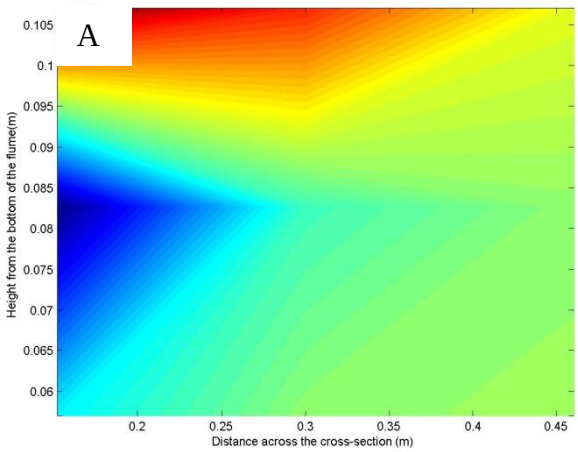
D-Sand Concentration Diagram for location 2 at Q =4.45E-3
E-Sand Concentration Diagram for location 1 at Q =4.56E-3
F-Sand Concentration Diagram for location 2at Q =4.56E-3

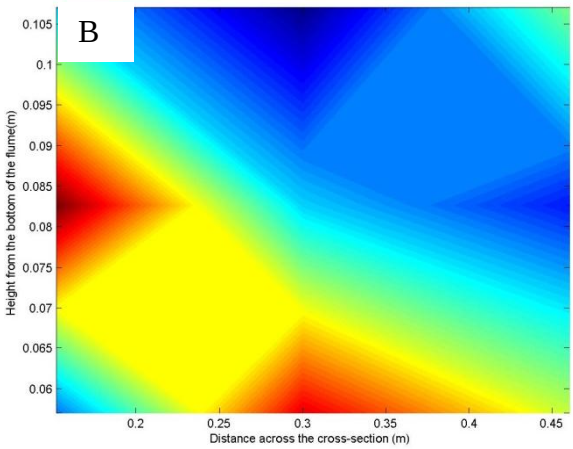




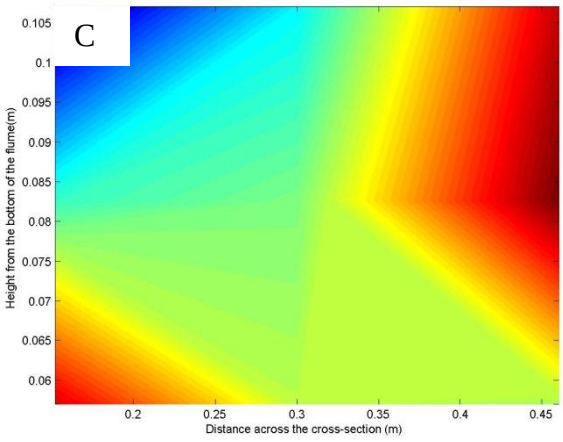


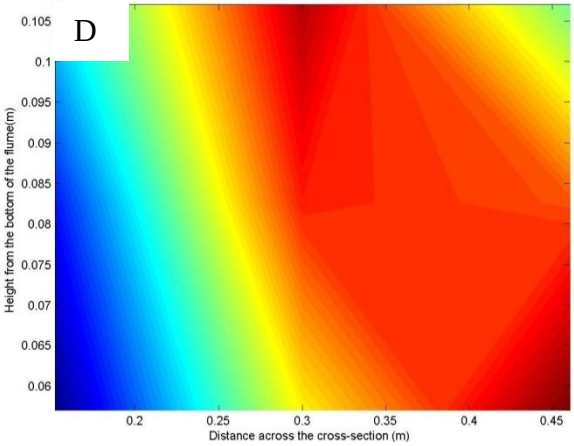
G-Sand Concentration Diagram for location 1 at Q =5.09E-3
H-Sand Concentration Diagram for location 2 at Q =5.09E-3



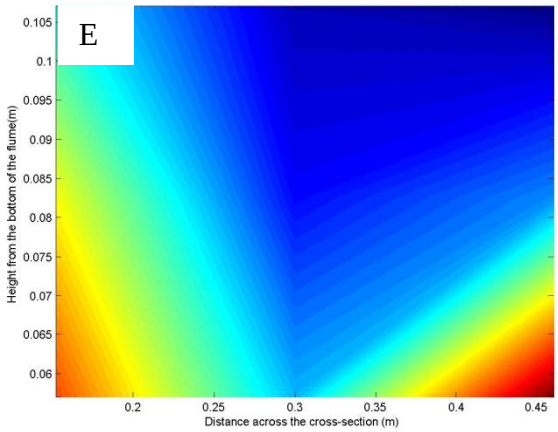


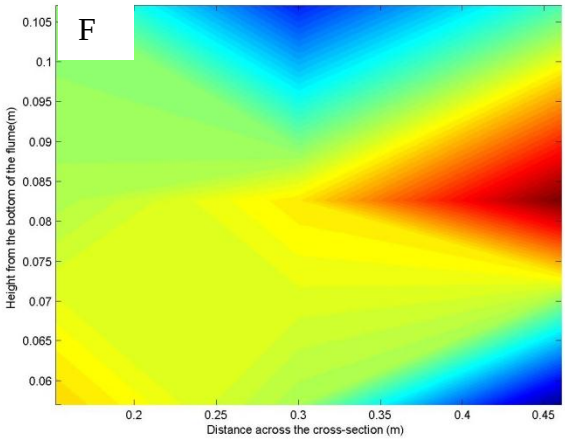
A-Sand-Silt Concentration Diagram for location 1 at Q =1.56E-3
B- Sand-Silt Concentration Diagram for location 2 at Q =1.56E-3
C- Sand-Silt Concentration Diagram for location 1at Q =2.45E-3

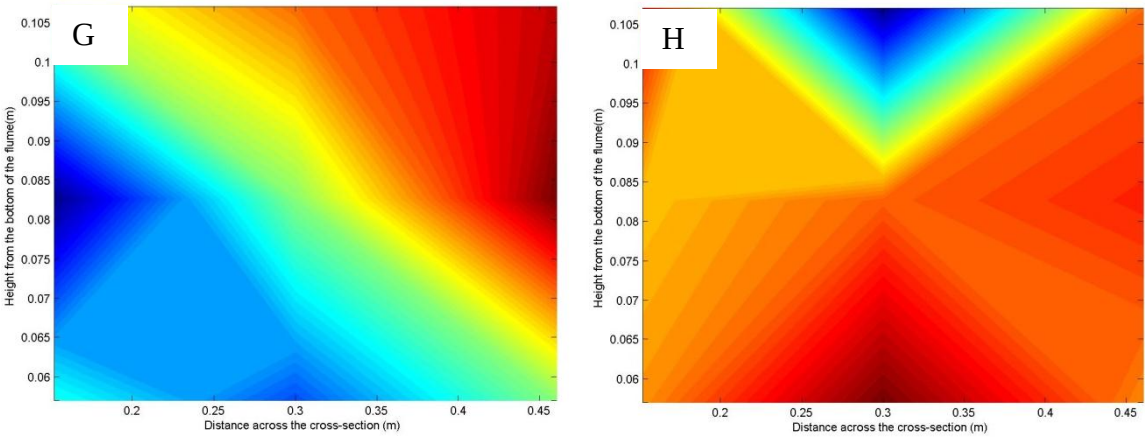




D-Sand-Silt Concentration Diagram for location 2 for at Q =2.45E-3
E- Sand-Silt Concentration Diagram for location 1 at Q =3.14E-3
F- Sand-Silt Concentration Diagram for location 2 at Q =3.14E-3

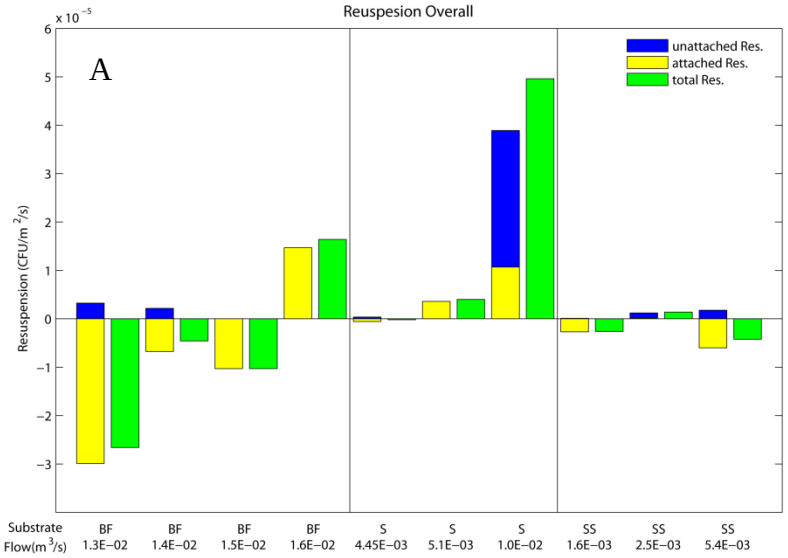




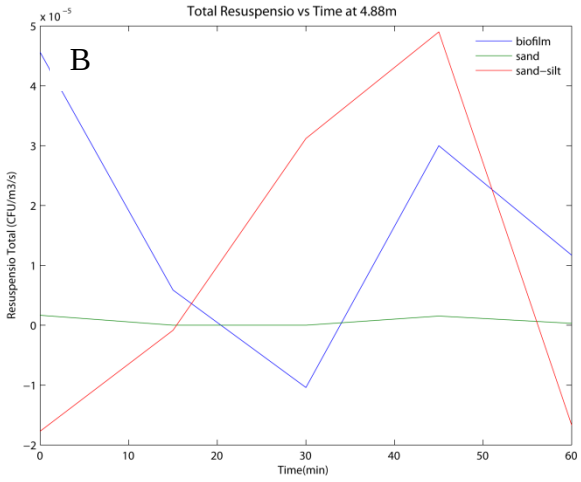


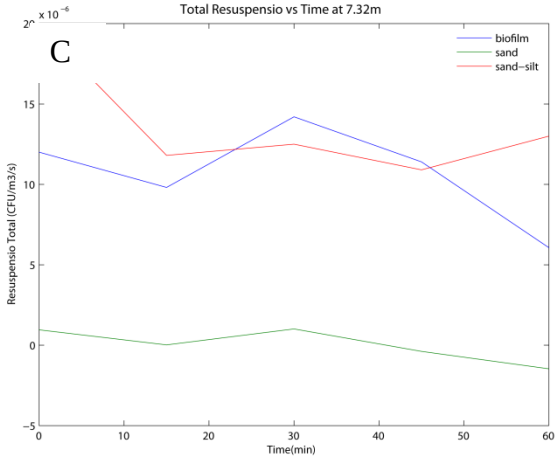
G-Sand-Silt Concentration Diagram for location 1 at Q =5.44E-3
H- Sand-Silt Concentration Diagram for location 2at Q =5.44E-3

Resuspension Overall and Total Resuspension Comparison to Time

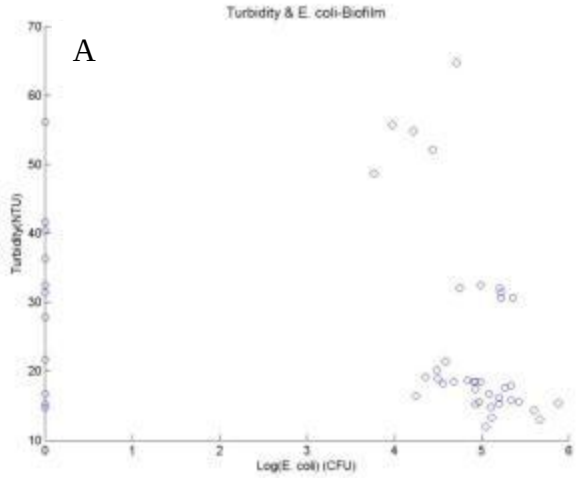


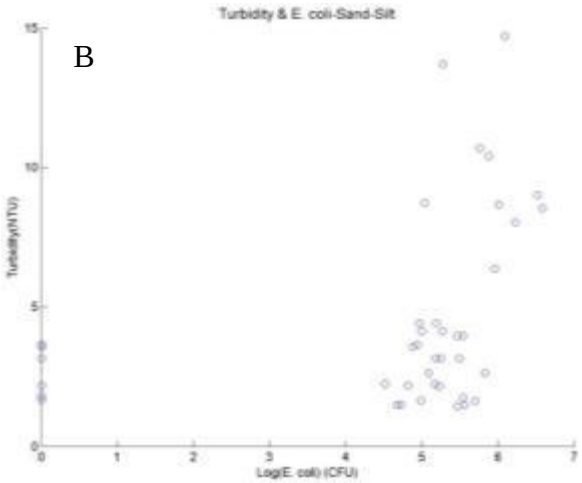
A-Resuspension overall graph, for all the different sediments separated by a line
B-Total resuspension in comparison to time for location 1
C- Total resuspension in comparison to time for location 2

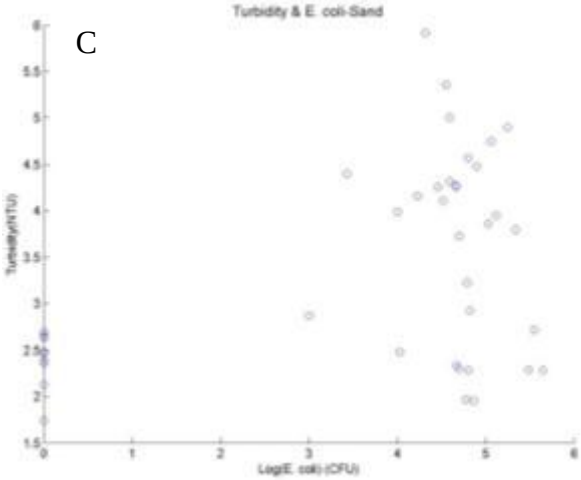




Turbidity Comparison to Attached *E. coli* Concentrations





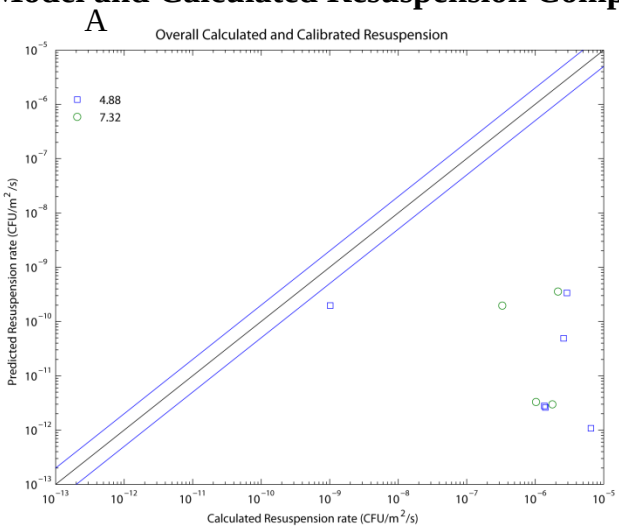


A-Turbidity and attached *E. coli* concentrations for Biofilm, no trend shown

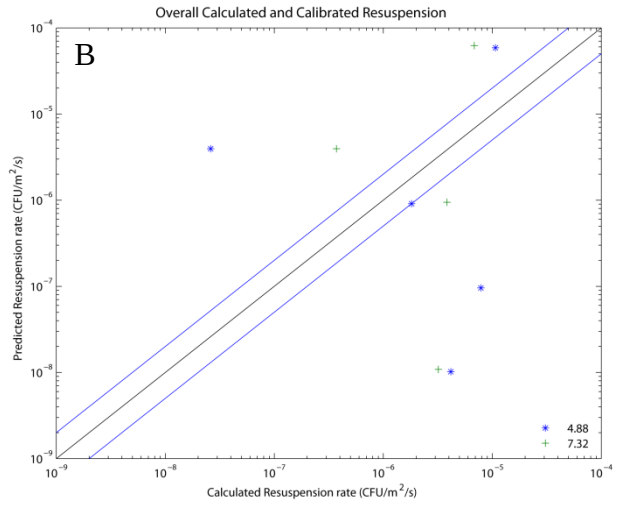
B- Turbidity and attached *E. coli* concentrations for Sand-Silt, no trend shown

C- Turbidity and attached *E. coli* concentrations for Sand, no trend shown

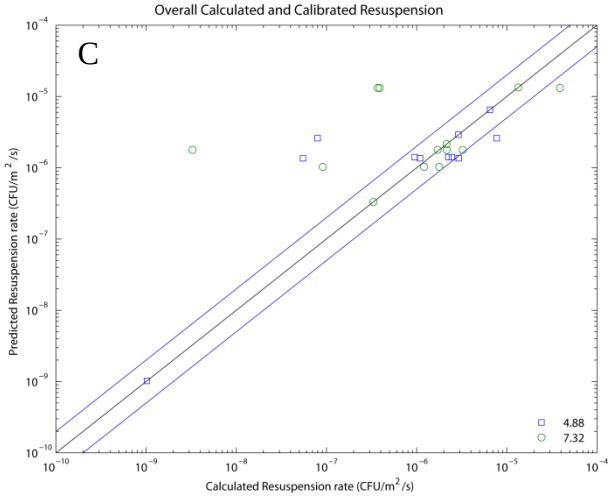
Model and Calculated Resuspension Comparisons



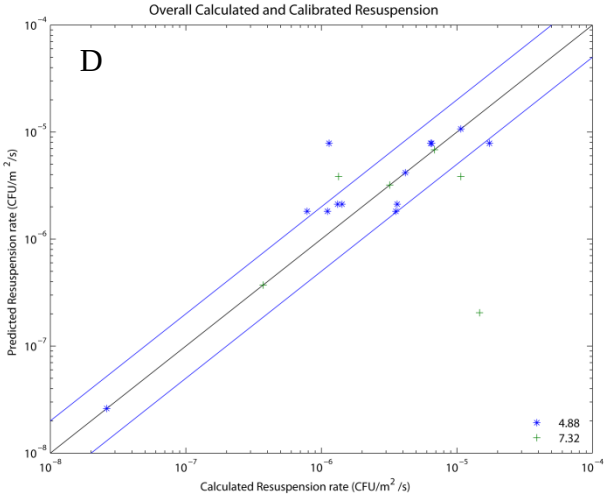
A-Resuspension comparison of physical average with the calibrated model with only Eou and b. The graph is only for the unattached fractions of resuspension.



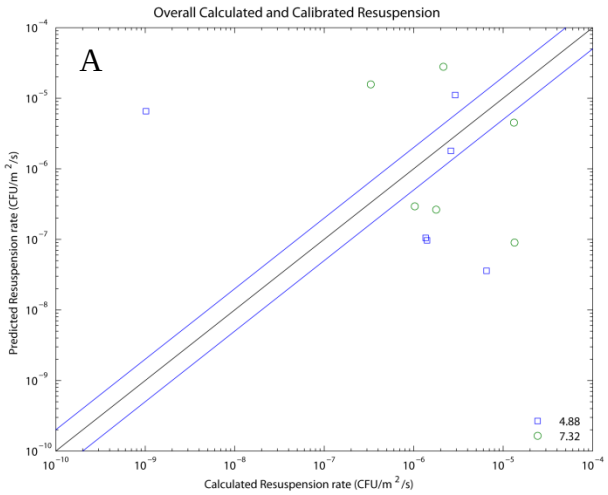
B-Resuspension comparison of physical average with the calibrated model with only Eou and b. The graph is only for the attached fractions of resuspension.



C-Resuspension comparison of physical with the calibrated model with Eou, b and bottom sediments calibrated n parameters. The graph is only for the unattached fractions of resuspension.

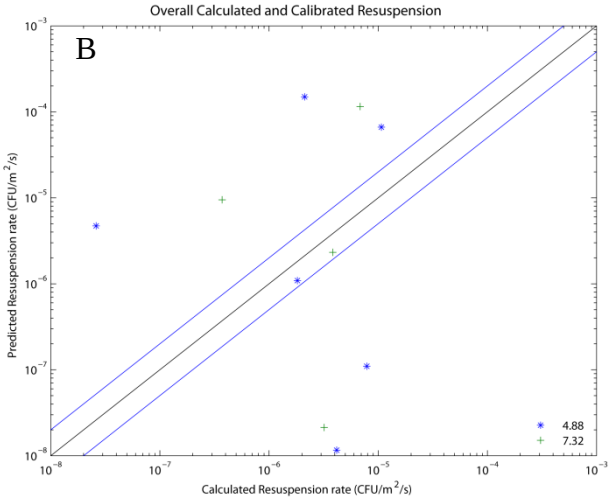


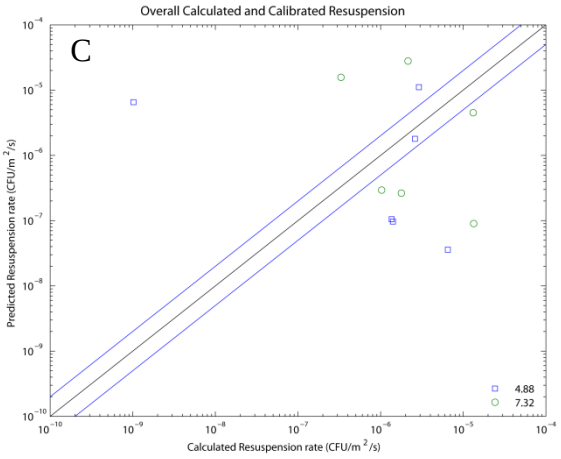
D- Resuspension comparison of physical with the calibrated model with Eou, b and bottom sediments calibrated n parameters. The graph is only for the attached fractions of resuspension.



A- Resuspension comparison of physical with the calibrated model with Eou, b and bottom sediments calibrated n parameters averaged for all bottom sedimentss and depths. The graph is only for the unattached fractions of resuspension.

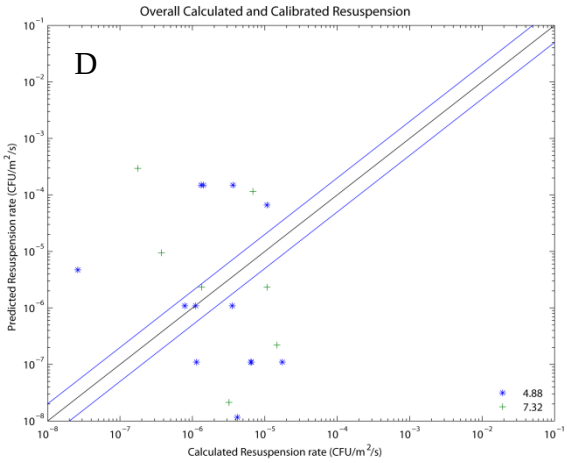
B- Resuspension comparison of physical with the calibrated model with Eou, b and bottom sediments calibrated n parameters averaged for all bottom sedimentss and depths. The graph is only for the attached fractions of resuspension.





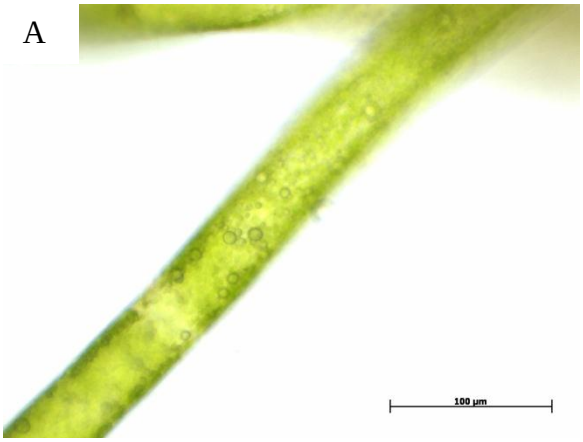
C- Resuspension comparison of physical with the calibrated model with Eou, b and bottom sediments calibrated n average parameters all bottom sedimentss and depth. The graph is only for the unattached fractions of resuspension.

D- Resuspension comparison of physical with the calibrated model with Eou, b and bottom sediments calibrated n average parameters for all bottom sedimentss and depth. The graph is only for the attached fractions of resuspension.

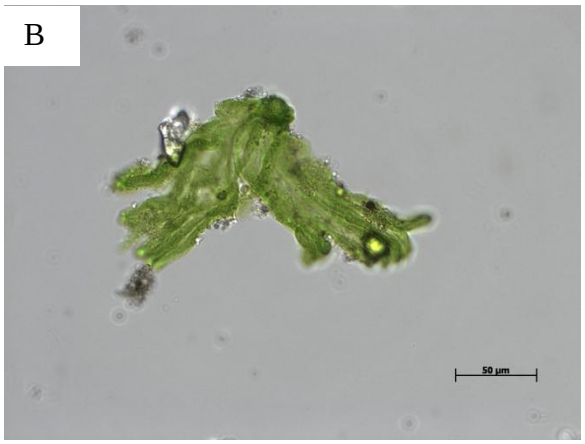


Bright Field Microscopy Images

A

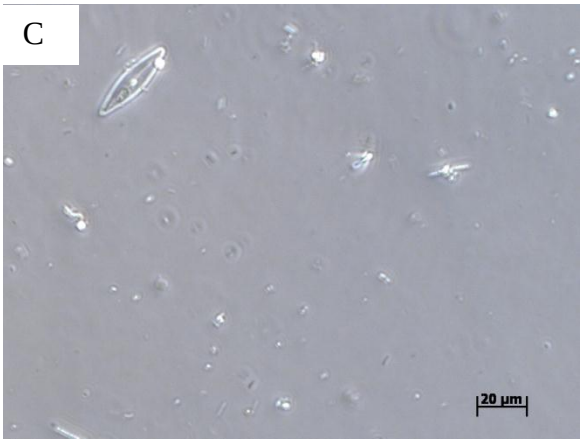


B



A- Blue green Algae
B- Blue Green Algae Diatom in water

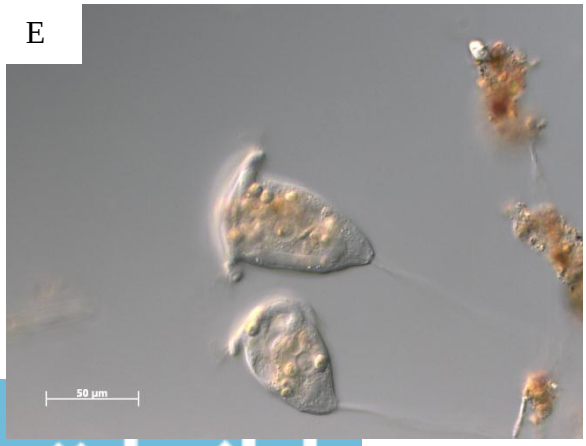
C



D

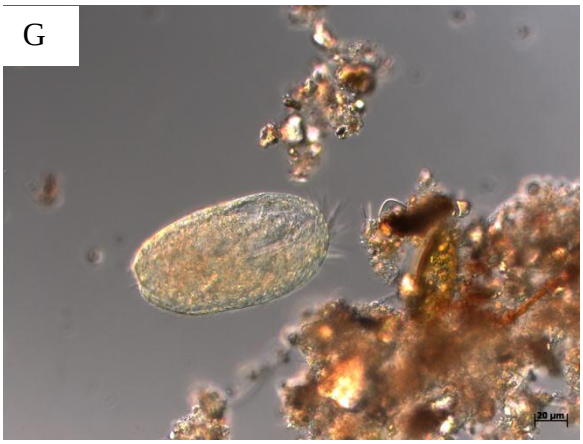
D- Blue green Algae
E- Attached Rotifers
F- Blue Green Algae

E

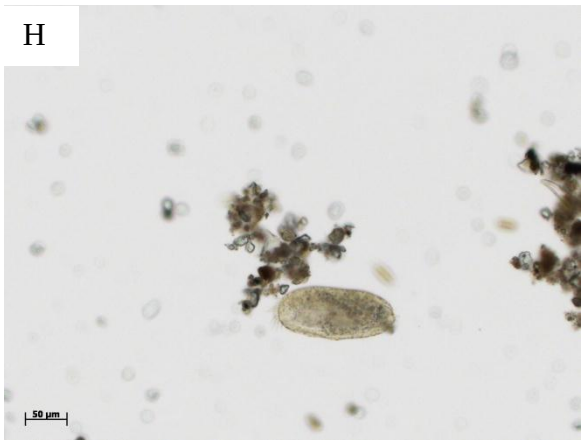


F

G

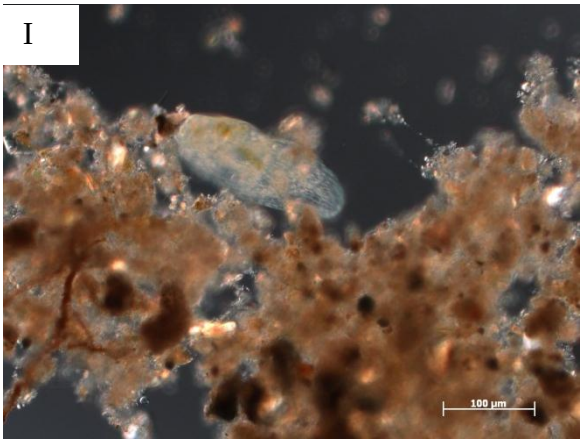


H

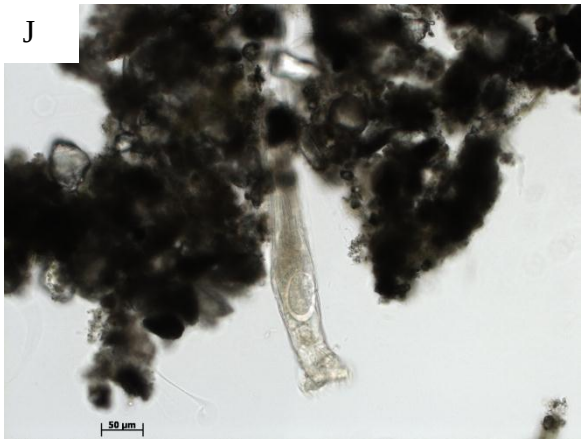


G- Rotifer in biofilm
H- Rotifer in biofilm
I-Rotiver in biofilm

I

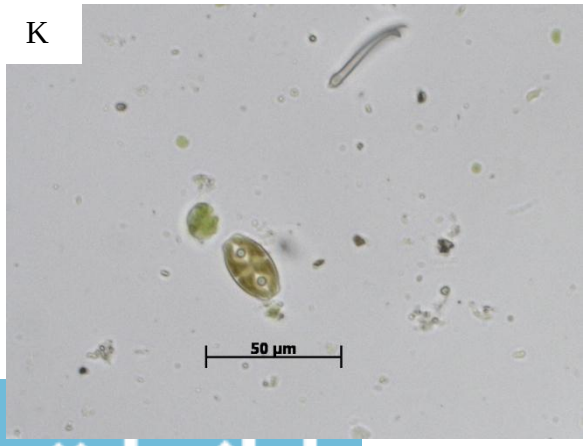


J



J- Rotifer attached to sediment
K- Diatom
L-Rotifer in water

K



L