The Effect of Coarse Gravel on Cohesive Sediment Entrapment in an Annular Flume

by

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Abstract

The amount and type of cohesive sediment found in gravel river beds can have important implications for the health of aquatic biota, surface/groundwater interactions and water quality. Due to landscape disturbances in the Elbow River watershed, increased sediment fluxes have negatively impacted fish habitat, water quality and water supply to the City of Calgary. However, little is known about the source of cohesive sediment and its interaction with gravel deposits in the Elbow River. This research was designed to: 1) quantify the transport properties (critical shear stress for erosion, deposition, porosity, settling velocity, density) of cohesive sediment and 2) evaluate the potential for coarse gravel to entrap cohesive sediment in the Elbow River.

A 5m annular flume was used to conduct erosion and deposition experiments using plane and coarse bed conditions. The critical shear stress for deposition and erosion of the Elbow River cohesive sediments was 0.115Pa and 0.212Pa, respectively. The settling velocity of the cohesive sediment had an inverse relationship between floc size and settling velocity for larger flocs, due to a decrease in floc density with increased size. Cohesive sediment moved from the water column into the gravel bed via the coupling of surface and pore water flow. Once in the gravel bed, cohesive sediments were not mobilized from the bed because the shear produced by the flume was less than the critical shear to mobilize the gravel bed. Using a model developed by Krishnappan and Engel (2006), an entrapment coefficient of 0.2 was determined for the gravel bed. Entrapment coefficients were plotted against substrate size, porosity and hydraulic conductivity, demonstrating a relationship between entrapment coefficient and these variables.

It was estimated that 864kg of cohesive sediment is stored in the upper 0.08m of a partially submerged point bar in the Elbow River. Accordingly, when flow conditions are sufficient to mobilize the gravel bed and disturb the amour layer, cohesive materials may be entrained and transported into the Glenmore Reservoir, where it will reduce reservoir capacity and may pose treatment challenges to the drinking water supply.

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Chapter 1. Introduction

1.1 Problem Statement

There is increasing global awareness regarding the environmental significance of the transport, storage, fate and effects of cohesive sediment in aquatic systems (Droppo *et al.*, 2000; Horowitz and Elrick, 1987; Jobson and Carey, 1989; Ongley *et al.*, 1992). Because of the need to understand the impacts of cohesive sediment and associated contaminants on aquatic biota (Ankers *et al.*, 2003; Droppo and Stone, 1994) and the physical loss of habitat through infilling of interstitial spaces with cohesive sediment in stream beds (Cobb *et al.*, 1992), an increasing number of recent experimental and field studies have advanced knowledge of cohesive sediment transport and storage mechanisms in aquatic systems (Droppo and Amos, 2001; Packman *et al.*, 2000; Rehg *et al.*, 2005; Stone and Krishnappan, 2003; Krishnappan and Engel, 2006; Krishnappan, 2007). Deposition of cohesive sediment in gravel bed streams can influence pore water chemistry and nutrient cycling (Grimm and Fisher, 1984; Nagorski and Moore, 1999; Worman *et al.*, 2002) as well as alter the porosity and conductivity of stream beds (Packman and MacKay, 2003).

In a study of Elbow River water quality related to water supply for the City of Calgary, Sosiak and Dixon (2004) reported that: 1) land use activities in the Elbow River basin may pose a potential risk to the water supply; 2) the Glenmore Reservoir may be at risk due to continued urban development pressures in the Elbow River basin; 3) increasing disinfectant demand at the Glenmore Water Treatment Plant has increased the production of disinfection by-products; and, 4) algal blooms in the reservoir have increased resulting in taste and odor problems in treated water. Sosiak and Dixon (2004) concluded that many of the water quality problems in the Glenmore Reservoir are directly related to land use change and its effect on the source, quality, transport and fate of cohesive sediment in the Elbow River basin. Accordingly, in order to understand and better manage the long term impacts of land use change on water quality and drinking water supply, there is a need to rigorously quantify processes that influence the in-stream source, entrapment, release and transport dynamics of fine sediment in the Elbow River. Currently no information is available regarding the entrapment dynamics of fine sediment in coarse gravel beds of the Elbow River.

The mountains of western North America are the source of drinking water for numerous cities and towns in North America (Pederson *et al.*, 2011). The discharge of rivers that originate in these high mountain environments is strongly influenced by the annual snow pack (Pederson *et al.*, 2011). Many of these source water regions are wholly or partially forested and susceptible to forest fires which can alter nutrient and sediment supply to the river (Silins *et al.*, 2008). Because of the high energy conditions in many of these river systems, river beds predominantly consist of coarse gravel (Wohl, 1962). Because of the similarities in river processes and form as well as their importance for water supply, knowledge gained regarding entrapment processes and entrapment coefficients may be broadly transferable.

1.2 Research Objectives

The objectives of this study are to:

1. Quantify the transport and depositional properties (critical shear stress for erosion and deposition, settling velocity and density) of Elbow River cohesive sediments experimentally in an annular flume with plane bed and coarse gravel bed conditions;
2. Evaluate the entrapment of cohesive sediment in gravel beds and processes that influence its remobilization from the gravel bed; and,
3. Quantify the entrapment ratio of gravel substrates from the Elbow River.

1.3 Literature Review

1.3.1 Nature of Cohesive Sediment

Wood and Armitage (1997) define fine sediment as materials <2 mm, which includes sand (<2000 to >62 µm), silt (<62 to 4 µm) and clay (<4 µm). For the purposes of this research, the term cohesive sediment is defined as materials <63 µm (Ongley *et al.*, 1992). Cohesive sediment has a high surface area to mass ratio, large cation exchange capacity (Mehta, 1989) and can flocculate in the water column (Lick *et al.*, 1992; Ongley *et al.*, 1992). Flocculation, the process of aggregation of smaller particles into a larger one (floc), is a dynamic process that influences particle size distribution in the water column (Lick *et al.*, 1992; Krishnappan, 2007). Floc density is dependent on floc size which in turn influences settling velocity (Lick *et al.*, 1992). Rates of particle aggregation and disaggregation are governed by environmental variables such as fluid shear stress, particle concentration, differential settling of particles, salinity, dissolved ions, pH, temperature and biological processes (Partheniades *et al.*, 1968; Lick *et al.*, 1992; Ongley *et al.*, 1992).

The potential of cohesive sediments to form flocs and influence particle transport dynamics in rivers increases the challenge of understanding how cohesive sediment interacts with streambeds of varying size class. Of particular importance in elucidating the interactions between suspended fine sediments and a streambed involves understanding the rate at which flocs settle onto a river bed (Krishnappan, 2007). The settling velocities of non-cohesive particles increase with increasing particle diameter (Lick *et al.*, 1992) but this does not hold true for flocs comprised of cohesive sediments (Krishnappan, 1990; Krishnappan *et al.*, 1999). Stone and Krishnappan (2003) reported "effective floc densities decrease as a function of floc size but after a certain size, floc-settling velocity decreases with the floc size due to the inverse relationship between floc size and effective density." Using an rotating annular flume, Krishnappan and Engel (2006) demonstrated that floc density decreased as a function of increasing floc size and that particles ~45µm in diameter could have a density similar to that of water. Accordingly, to determine floc settling velocity it is necessary to understand the relationship between particle density and diameter (Lick *et al.*, 1992; Stone and Krishnappan, 2003).

Settling velocity of spherical fine particles (diameter < 1mm) is described by Stokes Law, which states that settling velocity is proportional to the square of its diameter (d^2) and the dynamic viscosity of water at a given temperature,

$$v_s = \frac{gd^2}{18\mu}\left(\rho_p - \rho\right) \qquad [1]$$

where v_s is settling velocity, g is gravity, μ is dynamic viscosity, ρ_p is density of the particle and ρ is the density of water (Dingman, 2009). An underlying assumption of Stokes Law is that particles are spherical and particle density is assumed to be that of the solid. However, in aquatic systems flocs are not spherical and floc density can differ considerably from that of its constituent particles (Krishnappan, 2007). As floc porosity increases with increasing floc size, there is a corresponding decrease in density. Krishnappan and Engel (2006) found that settling velocity increased when flocs were small but above a critical diameter (20µm) and settling velocities decrease with increasing size. Accordingly, Stokes Law cannot be used to estimate the settling velocity of a floc and needs to be measured directly. It has been demonstrated that floc settling velocities are much lower (by a factor of 100) than predicted by Stokes Law (Lick *et al*., 1992).

Shear stress has a dual role in floc formation. Firstly, flocs formed under conditions of low shear stress tend to break up under higher shear stress. Secondly, flocs formed at high shear stress are more stable than those formed in low shear environments. Partheniades *et al*. (1968) suggested that only larger stronger flocs will settle on the bed, while weaker flocs break due to the shear stress at the bed and stay in suspension. Accordingly, there is an optimum shear stress for forming stable flocs, when aggregation and disaggregation are in balance (Stone and Krishnappan, 2003).

The flux of sediment deposition onto a streambed and the flux of sediment eroding from the bed determine the mass of suspended solids that will settle on/or into the bed (Krone 1962; Mehta and Li, 1998; Krishnappan, 2007). The properties of erosion and deposition differ between cohesive and non-cohesive sediments. For non-cohesive sediments, when bed shear stress is greater than the critical shear stress (the point at which particle incipient motion occurs), erosion and deposition occur simultaneously. For a steady state condition, when bed shear stress equals the critical shear stress, the rates of deposition and erosion are equal (Krishnappan, 2007). However, the erosion and deposition fluxes of cohesive sediments do not act simultaneously for all shear stress conditions. This is because as cohesive particles settle onto a cohesive bed, electrochemical and biological processes cause them to bind to the bed. Therefore, a greater shear stress for remobilization is required than the shear stress conditions under which it settled. Cohesive sediments therefore have two distinct critical shear stresses, one for deposition and one for erosion (Krishnappan, 2007).

Cohesive sediments consolidate over time when deposited on a bed. Bed age (period of consolidation) can influence the transport characteristics of the deposited sediment by altering the critical shear stress for erosion through compaction (Krishnappan and Engel, 1994; Milburn and Krishnappan, 2003). Bui (2000) describes bed consolidation as a three stage process whereby: 1) the floc structure gradually collapses, hindering setting (this process can occur over a period ranging from hours to days, where the change in bed elevation is proportional to time); 2) vertical “pipes” form in the bed structure (this process takes days to weeks and bed elevation becomes a function of $\sqrt{t}$, where t is the elapsed time); and, 3) pore volume decreases as flocs collapse which can take up to years to complete. Droppo and Amos (2001) investigated the vertical profile of cohesive sediment beds in Hamilton Harbour with an in-situ annular flume to determine the influence of bed consolidation on erosion rates. They found the bed was comprised of three primary layers associated with bed consolidation. The surficial layer was characterized as surficial fine-grained lamina (SFGL), described as a temporary, low-density, high-water-content, “fluffy” deposit or blanket over the existing bed which accumulates between erosion events (Droppo and Stone, 1994; Droppo *et al.*, 2001). The 2mm to 4mm thick surficial layer was bound together mainly through chemical and biological mechanisms and showed no sign of consolidation with depth. The next layer, which they refer to as the collapsed layer, was approximately 10mm thick and its density increased with depth due to self-weighting consolidation. The third and lowest layer in the sediment column was referred to as the consolidated bed and its density remained fairly constant with depth. Bui (2000) and Droppo and Amos (2001) have shown bed consolidation is a function of time and bed thickness.

In an investigation of the transport characteristics of Hay River sediment, Milburn and Krishanppan (2003) reported that the critical shear stress for erosion of this sediment increased with the consolidation period. They attributed the greater critical shear stress to the formation of biofilm growth during the seven day consolidation period. Biostabilization occurs when extracellular polymeric substances (EPS) produced by microbial, algal, fungal and other organisms increase the stability of cohesive sediment deposits (Droppo *et al.*, 2001; Black *et al.*, 2002). Droppo (2009) measured the critical shear strength of cohesive sediments from five individual water bodies for a variety of consolidation periods and bed shear stress. He found that consolidation time had a varying degree of influence on the erosion of the cohesive sediment bed but concluded biological processes play a strong role in controlling bed stability. Stone *et al*. (2010) study the influence of biostabilization on sediments from two Southern Alberta rivers and found greater spatial biofilm development on wildfire-affected stream sediments, resulted in critical shear stress for erosion 1.6 and 1.8 times greater than for unaffected sediments.

1.3.2 Cohesive Sediment Transport Models

Many sediment transport models are not fully developed to represent and predict the transport of cohesive sediment transport in rivers. In early models, it was assumed that fine grain sediments (<63 µm) were neither stored in or on the streambed in appreciable quantities but were predominantly transported in suspension as wash-load (Bagnold, 1966). Early transport models were developed based on the assumption that fine sediments were transported as a conservative parameter, allowing only for additions to the transported mass and did not account for settling or entrainment into the bed (Jobson and Carey, 1989). Lambert and Walling (1998) quantified fine sediment storage on and in the bed of the River Exe in the United Kingdom and reported that storage of sediment <63 µm accounted for a very small percentage (mean value of under one per cent) of the sediment budget of channel storage. Accordingly, they concluded that the river bed was not important for cohesive sediment storage and that fine sediment was conveyed efficiently through the system.

A number of studies have demonstrated that fine sediments are not suspended indefinitely but rather are deposited on and in river beds (Partheniades *et al*., 1966; Mehta and Li, 1988; Lick *et al*., 1992). More recent studies demonstrate that the storage of fine sediment in some gravel bed streams can be significant (Petticrew and Biickert, 1998; Packman and MacKay, 2003; Krishnappan, 2007). While these empirical studies provide quantitative estimates of the mass of cohesive sediment stored in river beds, they provide little to no information regarding transport mechanisms governing the deposition, storage and release of cohesive sediments into gravel beds.

Early sediment transport models were developed to evaluate the transport of non-cohesive sediment. Initially, these models did not include parameters to represent floc formation and transport. Knowledge of the complex and unique nature of cohesive sediment transport has been predominantly advanced through carefully controlled laboratory studies in flumes (Krishnappan and Engel, 2006). Accordingly, these studies have served to identify and quantify primary processes that govern cohesive sediment transport in aquatic systems. These processes include flocculation and its influence on settling velocity, the effects of critical shear stress for deposition and erosion and the establishment of steady state concentrations based on the relationship between shear stress and aggregation and disaggregation of flocs at the bed (Partheniades *et al*., 1962, 1966, 1968). Building on this knowledge, models incorporated terms representing the advective and dispersive flux terms of simultaneous deposition and erosion of cohesive sediments (Lee *et al.*, 1981; Krishnappan, 2007). While advancements in cohesive sediment transport models have been made, they are based primarily on results of laboratory studies and are very seldom verified under field conditions (Bui, 2000).

The development of cohesive sediment transport models has progressed in step with the understanding of cohesive sediment properties. Krone (1962) developed the following deposition equation for conditions where bed shear stress (τ) is less than the critical shear stress for full deposition ($\tau_{d,full}$):

$$Q_d = P_d \omega c \text{ for } \tau \leq \tau_{d,ful} \qquad [2]$$

where Q_d is deposition rate, P_d is the deposition probability, ω is settling velocity and c is the suspended sediment concentration. The variable P_d represents the probability that particles will bind to the bed and not be re-entrained into the flow. The probability that a portion of the sediment settling on the bed will be eroded from the bed due to the bed shear stress is expressed as

$$P_d = 1 - \tau/\tau_{d,full} \text{ for } \tau \leq \tau_{d,full} \qquad [3]$$

Most current models use a time-rate decrease ($\partial C/\partial t$) of suspended sediment concentration to determine a deposition rate. Mehta and Li (1998) provide an equation for sediment deposition building on Krone (1962):

$$h\frac{\partial C}{\partial t} = -p\omega_{s1}C \qquad [4]$$

where h is the flow depth, p is the probability of deposition, ω_{s1} is the settling velocity of a uniform sediment, and C is the concentration of the suspended sediment. The probability (p) is an expression of the influence bed shear stress has on the deposition rate

$$p = 1 - \frac{\tau_b}{\tau_c} \qquad \tau_b < \tau_c \qquad [5]$$

$$0 \qquad \tau_b \geq \tau_c \qquad [6]$$

where τ_b is the bed shear stress and τ_c is the critical shear stress for deposition.

Sediment erosion from the bed has been expressed as the mass of sediment mobilized by bed shear stress (Bui, 2000):

$$E = \varepsilon(\tau_b - \tau_s) \qquad [7]$$

where E is the erosion rate, ε is the erosion coefficient, $\tau_b$is the bed shear stress and τ_s is the bed shear strength. If advective and dispersive parameters (deposition and erosion parameters) associated with cohesive sediment transport are considered simultaneously, a mass balance equation can be used to determine the transport of cohesive sediment. Teisson (1997) developed the following governing equation:

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}_i \frac{\partial \bar{c}}{\partial x_i} + \frac{\partial (w - w_s)\bar{c}}{\partial z} = -\frac{\partial \overline{(u_i' c')}}{\partial x_i} + S(x, y, z, t) \qquad [8]$$

$$x_i = x, y, z \; and \; u_i = u, v, w$$

where $\bar{c}$ is the mean concentration of sediment in suspension, t is the time, $\bar{u}_i$ and u_i are the mean and instantaneous flow velocities respectively, x_i represents the co-ordinate axes, w is the vertical velocity component, z is the vertical co-ordinate axis, u_i' and c' are fluctuating velocity components and fluctuating sediment concentration respectively, w_s is the settling velocity of the sediment particle, $S(x, y, z, t)$ is the sediment source or sink term within the solution domain other than the boundaries, v is the flow velocity in the y direction, and w is the flow velocity in the z direction. The equation takes into account advective (settling) and dispersive (mobilized into the flow domain) fluxes and sediment sources and sinks (Krishnappan, 2007). When calculating the transport of cohesive sediments, it is assumed that there is no external input of sediment (advective and dispersive fluxes are equal) at the free surface boundary (water surface). At the sediment-water interface it is assumed that the settling and dispersive fluxes are balanced by the net amount of sediment entering from the bed into the flow domain (Krishnappan, 2007). Of all the required modeling parameters, settling velocity has the greatest influence on the model output, but it can be difficult to calculate due to the physical, chemical and biological properties of cohesive sediment and the water column (Krishnappan, 2007).

1.3.3 Entrapment of Cohesive Sediments

Studies of fine sediment interaction with stream beds have been reported in the literature. Diplas (1947) observed that entrapment of fine sediment is dependent on the suspended sediment concentration and that entrapment will continue until a clogging layer is formed. Entrapped sediments remain in the stream bed thereafter and do not interact with the flow until the bed is mobilized. Einstein (1968) observed entrapment of fines (silt-sized particles) in gravel beds. He reported that when fine sediments enter the stream bed with pore water over time, suspended sediment concentrations in the water column approach zero as the sediments became entrapped. Einstein (1968) also found that fine sediments remained in the bed until a critical threshold shear stress occurred to mobilize the gravel bed.

More recent studies have investigated entrapment of cohesive sediment in sand beds. Rehg *et al*. (2005) demonstrated that the mobilization of a sand bed with bed-forms (dunes) increased the amount of suspended sediments entrapped in the bed. They attributed increased sediment entrapment to bed mobilization that prevented the formation of a clogging layer in the upper surface of the streambed. Clogging layers formed under static bed conditions through the infilling of the bed pore voids when clay particles are pumped advectively into the bed (Rehg *et al.*, 2005). The clogging layer cuts off the advective pumping process and correspondingly reduces additional infiltration of suspended fine grain sediments into the streambed. Rehg *et al*. (2005) further reported that under shear stress conditions that cause a sand bed to be mobilized a clogging layer was prevented by the mobile bed, which results in continual pumping of fine sediment into the bed. Schalchli (1992) conducted a series of flume experiments using bed sediments collected from the Langeten River in Switzerland. He reported that the hydraulic conductivity of the streambed was reduced when a clogging layer was formed near the surface of the bed. This process reduced the hydraulic conductivity of the bed but under conditions of high shear stress the bed was remobilized. Accordingly, under these conditions the clogging layer was removed and the hydraulic conductivity of the bed was increased. Krishnappan and Engel (2006) studied the entrapment potential for gravel beds under both low and high shear stress conditions and found they were similar as a clogging layer did not form. This observation suggests that larger void ratios associated with gravels are sufficient to prevent the formation of a clogged layer under the sediment concentrations used in their study. Accordingly, gravels with large void spaces have a higher potential to entrap fine grain sediments, even under low flow conditions.

Several studies highlight the importance of bed form and bed mobility on the entrapment of cohesive sediments (Schalchli, 1992; Krishnappan and Engel, 2006; Rehg *et al*., 2005). Packman *et al*. (2000) developed a bed-form induced advective pumping model to describe the infiltration potential of fines into a streambed comprised of sand. The model predicted that bed-forms (dunes) could increase hydraulic gradients on the leading face of dunes which increases the hydraulic pressure of water forced or “pumped” into the streambed in a regular pattern corresponding to dune spacing. Suspended sediments within the water column are forced by this mechanism into the streambed along with the surface water, resulting in the transfer of suspended sediments from the water column into the bed. Packman *et al*. (2000) used the advective pumping model to predict the rate at which suspended sediments were trapped by the bed, and Packman and MacKay (2003) used the entrapment model to study the influence of suspended sediments on the rate of hyporheic exchange within the streambed. They found that clays preferentially infiltrate into gravel beds where zones of high advective pumping occur. When void spaces within the top layer are filled with clay, a clogging layer is created which inhibits hyporheic exchange and further entrapment of fine sediment. Packman and MacKay (2003) concluded that relatively small amounts of suspended sediments can clog a sand streambed and inhibit hyporheic exchange. They also suggested that bed forms were required to advectively pump fine sediments into a sand bed and this pumping action would not occur under conditions of plane bed.

While bed forms may be required for the entrapment of cohesive sediments in a sand bed, Nagaoka and Ohgaki (1990) found that the exchange between stream flow and pore water can be greatly enhanced in gravel beds where there is direct coupling of stream and pore water flows due to turbulence. They reported that turbulent stream flow over a coarse bed is sufficient to promote solute transport into a gravel bed lacking bed form (diffusion). This observation suggests that the roughness of a gravel bed can induce entrapment without the requirement of bed forms. Packman and Salehin (2003) described advective hyporheic exchange in flat gravel beds and attributed this phenomenon to periodic pressure variations along the bed surface produced by turbulent flow induced by bed roughness. Packman *et al*. (2004) studied the exchange of surface water and pore water flow within gravel beds with and without bed forms. They found that, “the exchange of surface and subsurface water was highly dependent on the stream velocity, which supports the idea that pore water flow in a gravel bed is tightly coupled with the stream flow regardless of the bed topography.” Packman *et al.* (2004) also concluded that in coarse sediment deposits such as gravels, the high permeability and small topographical irregularities on the order of the grain diameter can cause flow separation that provides sufficient head differences to drive advective pumping of flows.

Krishnappan and Engel (2006) used an annular flume to study the entrapment of fine particles within streambeds of various mean diameters that ranged in size from sand (D_{50} = 1 mm) to fine gravel (D_{50} = 8mm) under varying conditions of shear. They demonstrated that the majority of suspended fine sediments were trapped in the coarser bed (gravel) matrix and were unavailable for resuspension under the applied shear stresses used in the experiment. This observation contrasted with the sand bed which resulted in far less suspended sediment removed from the water column. They reported the entrapment potential of sands increases with increasing shear and attributed this observation to increased bed mobility and bed-form development (i.e. the bed became mobile and dune bed forms were produced). They postulated that the presence of bed-forms resulted in the development of advective pumping mechanisms, which ‘pumped’ the fine grain sediment into the bed.

Krishnappan and Engel (2006) were the first to use the results of entrapment experiments to develop an entrapment ratio based on substrate size. The addition of an entrapment ratio into the advective and dispersive mass balance equation is required for a porous bed because entrapped sediments are no longer available as a dispersive function.

They included the entrapment coefficient into the governing equation for the settling stage using a one dimension mass balance equation (Equation [9]):

$$\frac{\partial C_k}{\partial t} + w_k \frac{\partial C_k}{\partial z} = \frac{\partial}{\partial z}\left(\Gamma \frac{\partial C_k}{\partial z}\right) + S \qquad [9]$$

where, C_k is the concentration of the cohesive sediment (suspended sediment) in size fraction k, $w_k$is the settling velocity of that fraction and Γ is the dispersion coefficient in the vertical direction, t is the time axis, z is the coordinate axis in the vertical direction, and S is the source/sink term. The boundary conditions used for the settling stage are:

at the free surface:

$$- w_k\ C_k - \Gamma\ \partial\ Ck\partial z \qquad [10]$$

at the bed:

$$-w_k C_k - \Gamma \frac{\partial C_k}{\partial z} = q_e + q_d + q_{entrap} \qquad [11]$$

where, q_e represents the quantity of sediment eroded from the bed due to flow and entrained into the water column, q_d represents the quantity of sediment that can settle to the bed and stays at the bed as deposited sediment, and $q_{entrap}$was included by Krishnappan and Engel (2006) as an entrapment component in the bed boundary condition. The entrapment component is expressed as:

$$q_{entrap} = \alpha w_s C_b \qquad [12]$$

where α is a proportionality constant described as the entrapment coefficient, w_s is the settling velocity of the particles and C_b is the boundary concentration. The entrapment coefficient is believed to be a function of the gravel bed porosity, thickness of the gravel bed layer and the permeability of the substrate. Krishnappan and Engel (2006) found the results of the entrapment model agreed very well with measured values indicating a potential utility of using entrapment coefficients for various size fractions of bed substrates. Currently entrapment ratios have been determined for only a limited number of homogenous bed substrate types. Determining additional entrapment ratios using various substrate sizes distributions is required to fully evaluate the functionality of using entrapment ratios to predict a bed's entrapment potential.

1.3.4 Mobilization of Cohesive Sediment from Coarse Beds

Current research suggests cohesive sediments remain entrapped in a gravel bed until a sufficiently large flow occurs which generates a competent shear stress exceeding the critical shear stress of the gravel armor layer and the bed is mobilized (Diplas, 1947; Enstein, 1968; Schalchli, 1992; Rehg *et al.*, 2005; Krishnappan and Engel, 2006). A recent study describing bed dilation (changes bed elevation, increasing or decreasing respectively, in the absence of bed mobilization) and contraction found the release of fine sediment from a gravel bed is complex (Marquis and Roy, 2012). Marquis and Roy (2012) employed a variety of methods to measure bed load transport and bed mobility, including surveying bed elevation change, bed activity tags and bed load traps. The objective of their study was to understand the dynamics of the bed and its relationship to bed load transport under a variety of flood conditions. The study confirmed gravel bed dilatation and contraction occurred during smaller flood events and has implications for the release of cohesive sediments from a stable gravel bed. Marquis and Roy (2012) found that when a bed contracted there was a subsequent increase in fine sediment (sand) in the bed load traps, indicating the fine sediments comprising the bed matrix are mobilized from the bed as the framework particles reorganized and packed together. If cohesive sediments are entrapped within the sand matrix as previously reported (Schalchi, 1992; Rehg *et al.*, 2005; Krishnappan and Engel, 2006), it will likely be mobilized in conjunction with the fine sediment (sand) during the process of bed contraction.

1.3.5 Effects of Cohesive Sediment on Biological Processes

Gravel streambeds support a range of biological processes that include nutrient and geochemical cycling (Grimm and Fisher, 1984; Harvey *et al.*, 2003), habitat for benthic macro-invertebrates and fish spawning (Pugsley and Hyne, 1986; Montgomery *et al.*, 1996), hyporheic zone dynamics (Kasahara and Wondzell, 2003), stream morphology (Julien, 2002; Kington, 1998) and sediment and nutrient storage (Hoey, 1992; Krishnappan and Engel, 2006; Schalchli, 1992). These ecological processes are complex, diverse and sensitive to perturbations from sedimentation and entrapment of cohesive sediment (Lemly, 1982; Soulsby *et al.*, 2001).

The mixing of surface and subsurface water within a streambed can strongly influence the exchange of fine sediments, nutrients, oxygen and geochemical processes (Boulton *et al.*, 1998; Brunke and Gonser, 1997). The pumping of surface water into and out of the bed is critical to biological processes in gravel bed streams (Grimm and Fisher, 1984; Brunke and Gonser, 1997). These include: 1) the spawning success of fish such as migratory salmon (Geist, 2000; Hanrahan, 2008) where the exchange of surface water and groundwater flux maintains oxygen and temperature controls on egg development (Brunke and Gonser, 1997; Soulsby *et al.*, 2001; Malcolm *et al.*, 2004; Malcolm *et al.*, 2005); and, 2) the establishment and diversity of the benthic invertebrate community within a river (Richards and Bacon, 1994; Stubbington *et al.*, 2009).

High sediment loads can cause interstitial voids to fill and clog the top layer of gravel beds, ultimately covering the streambed (Brunke, 1999). This process is referred to as colmation and can result in reduced available habitat and form a thin seal below the armour layer that disconnects surface flow from hyporheic water (Brunke, 1999) that many lotic benthic invertebrates depend upon (Anderson and Wallace, 1984). Accordingly, this process reduces the diversity of the benthic invertebrate community and increases the number of pollution tolerant species (Lemly, 1982; Nerbonne and Vondracek, 2001). When gravel beds are covered with fines and transition to a more homogenous habitat type (Diplas and Parker, 1992; Walters *et al.*, 2003), fish community richness decreases and the number of more tolerant assemblages increase (Sutherland and Gardiner, 2002). Excessive sedimentation rates in streams reduce fish recruitment through the smothering of fish eggs, particularly those deposited within the voids of gravel stream beds (e.g. numerous cyprinids and walleye) or in fish (salmonid) spawning beds known as redds (Crouse *et al.*, 1981; Lisle and Lewis, 1992; Doeg and Koehn, 1994; Nerbonne and Vondracek, 2001).

Julien and Bergeron (2006) studied the effects of particle size classes on the survival of multiple embryonic developmental stages of Atlantic salmon. They found that while silts and clays represented only a small fraction of the sediment mass within incubation baskets, these materials most strongly affected the survival of the pre-eye and eyed stages of eggs (i.e. the earliest development stages). The change in egg survival was attributed to the ability of silts and clays to adhere to the eggs, creating a thin coating which inhibited the exchange of oxygen. Greig *et al.* (2005) also identified a similar effect with clay and reported that only a small fraction of clay was needed to impair egg survival. These studies highlight the potential negative impacts that fine sediments <63 µm can have on salmonid spawning success and underscores the need to better understand erosion and deposition dynamics between the cohesive sediments and coarse gravel bed streams.

1.3.6 Effects of Cohesive Sediment on Reservoirs

Nutrients bound to cohesive sediment are important to the ecology of lacustrine systems (Nowlin *et. al*, 2005) and can alter the productivity of lakes and reservoirs (Correll, 1998). Of particular importance is the transport of phosphorus, an essential element for life and often considered the limiting nutrient for primary production (Correll, 1998). With increasing phosphorus transport into a lake or reservoir, the system will progress from a low productivity oligotrophic condition to a productive mesotrophic condition and eventually to an enriched eutrophic condition (Correll, 1998). In recent years, an increase in nutrient loading within the Glenmore Reservoir has resulted in an increase in primary production, affecting the water quality in the reservoir (Sosiak and Dixon, 2004).

Eutrophication of a reservoir leads to increased algae growth and degraded water quality (Walker, 1983). When a reservoir such as the Glenmore Reservoir is a source for drinking water, nutrient enrichment can create water quality issues, requiring attention from treatment plant operators. Walker (1983) provides a number of direct impacts resulting from nutrient enrichment of a reservoir:

- Increases in particulate organic substances such as phytoplankton, zooplankton, bacteria, fungi and detritus;
- Algal populations shift toward more undesirable types (e.g., blue-greens);
- Increases in dissolved organic compounds that a) impart taste and odors, b) increase colour, c) are potential organo-halide precursors, d) provide substrate for bacterial growth in treatment plants and distribution systems;
- Increases in pH and its daily fluctuations; and
- Depletion of oxygen in the sediment-water contact area, causing the release of hydrogen sulfide, ammonia, phosphorus, iron, manganese, other metals, methane and other reduced organic compounds into the water column.

Walker (1983) also provides a list of direct effects on water treatment facilities, distribution systems and treatment costs:

- Hindrance of floc formation by dissolved organics;
- Increased chemical and operation costs for pH control;
- Increased clogging with algae and other particulates;

- Reduced filter run times;
- Increased water loss and energy costs in backwashing;
- Increased chlorine demand owing to organic matter and ammonia;
- Increased formation of chlorinated hydrocarbons, including trihalomethanes, resulting from reaction of chlorine within dissolved organic;
- Increased taste-odor problems owing to organic decomposition; and,
- Regrowth of bacteria owing to increased organic content.

Phosphorus has been identified as one of the primary nutrients of concern related to algal growth, water quality degradation and increased water treatment costs at the Glenmore Reservoir (Sosiak and Dixon, 2004). Due to it's a high affinity for binding to fine sediments (Nowlin *et. al*, 2005), understanding the transport of cohesive sediments from the Elbow River to the reservoir is critical to understanding the mass balance of phosphorus within the impoundment.

1.4 Summary

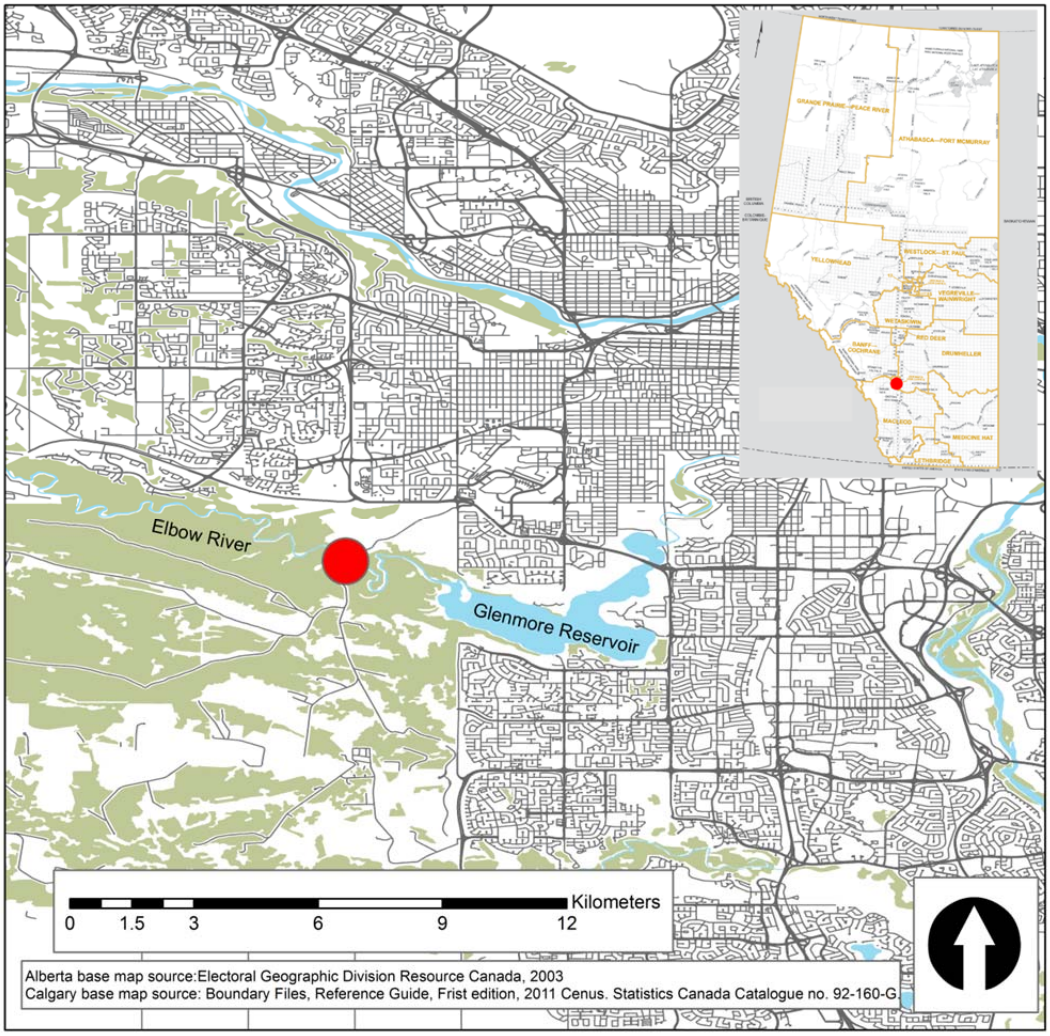
Mechanisms governing the interaction of cohesive sediments with gravel beds are complex and require more rigorous quantification, particularly in natural channels. Uncertainty exists regarding the magnitude of conveyance losses, the significance of remobilization from temporary storage as well as the duration and magnitude of long term storage within river channel systems (Lambert and Walling, 1998). While several recent advances have improved our mechanistic understanding of fine sediment entrapment and interactions with coarse bed streams, several major research gaps exist.

This study examines mechanisms of cohesive sediment entrapment in a laboratory flume using bed gravels, cohesive sediment and water collected from the Elbow River. The goal of this research is to understand and quantify cohesive sediment interactions with coarse gravel beds to more closely mimic natural river conditions in a laboratory flume. The study builds on earlier entrapment studies (Krishnappan and Engel, 2006) to advance the entrapment ratio concept.

Chapter 2. Methods

2.1 Experimental Design

The goal of this research was to rigorously quantify cohesive sediment transport dynamics in an annular flume and the role a gravel bed plays on fine sediment transport and entrapment. To achieve this goal, two sets of experiments were conducted in the 5m diameter annular flume located at the National Water Research Institute (NWRI) in Burlington, Ontario. The experiments included: 1) cohesive sediment erosion and deposition experiments at varying conditions of shear stress and initial sediment concentrations using a plane bed; and, 2) cohesive sediment erosion and deposition experiments at varying conditions of shear stress with a gravel bed. Water, gravel and cohesive sediments were collected in the early fall 2011, at the Weasel Head Trail foot bridge on the Elbow River in the City of Calgary, Alberta (Figure 2.1) and shipped to the National Water Research Institute at the Canadian Centre for Inland Waters (CCIW) in Burlington, Ontario. The fieldwork was conducted during low flow conditions to maximize the collection of fine sediment.



Alberta base map source:Electoral Geographic Division Resource Canada, 2003
Calgary base map source: Boundary Files, Reference Guide, Frist edition, 2011 Cenus. Statistics Canada Catalogue no. 92-160-G.

Figure 2.1 Sediment and Water Collection Site at the Weasel Head Foot Bridge on the Elbow River Upstream from the Glenmore Reservoir in the City of Calgary, Alberta.

2.2 Cohesive Sediment Sampling

Cohesive sediment and river water were collected from the Elbow River using an inverted cone sampler (Milburn and Krishnappan, 2003). The sampler consists of an inverted cone fitted with a propeller that re-suspends fine sediment deposits on the river bed (Figure 2.2 and 2.3). The sampler is fitted with a weight to stabilize it on the stream bed against flow and is moved along the river bed during sampling. Water and dislodged sediment were pumped directly into 100L sample barrels (a total of eleven were filled) and transported to NWRI. Barrels were placed in refrigerated storage at NWRI for a period of approximately two and half months to allow the fine sediments to settle to the bottom of the barrels. The water was decanted from the barrels and retained for the flume experiments. Fine sediment deposited on the bottom of the barrels was removed and filtered through a 64µm screen. The filtered fine sediments were combined with Elbow River water to prepare slurry of cohesive sediment. The slurry was injected into the flume to create the suspended sediment mixture used in the deposition and erosion experiments.

Figure 2.2 Inverted Cone Sampler used to Collect Cohesive Sediment and Water from the bed of the Elbow River.

Figure 2.3 Underside of the Inverted Cone Sample Showing the Impeller use to Dislodge Fine Sediment from the River Bed and the Water Intake Port.

2.3 Gravel Bed Sampling

Representative samples of surface pavement layer were collected from an area of approximately 550m^2 on a partially exposed gravel point bar. The surface pavement layer is operationally defined in this research as the depth of substrate equal to the average diameter of the gravel found directly on bed surface (Bunte and Abt, 2001). This layer was collected to a depth of approximately 30mm with a shovel and placed in plastic 10L buckets. The volume of stone required for the flume experiment was calculated prior to the field collection and in total, approximately 750kg of gravel was collected and shipped to NWRI. The samples were sufficient to create a 0.08m thick gravel bed in the rotating flume.

Preparation of the gravel for entrapment experiments included washing and sieving the materials five times using a SWECO Vibro-Energy Separator®. It was determined by visual inspection that the gravel was sufficiently clean after four cycles and contained no fine sediments. A 10mm screen was used to retain only clean sediments larger than 10mm.

Core samples were collected from an exposed point bar using a 100mm inside diameter PVC pipe driven into the point bar to a depth of 0.08m. Sediments outside the tube were removed and a plate was slid under the bottom of the sampler to capture the contents. A second plate was placed on the surface of the sediments in the tube and the tube was packed with foam, before caps were placed on the top and bottom of the tube. Core samples were analyzed for sediment size distribution in the lab (see Section 2.6).

2.4 Description of the Rotating Circular Flume

Sediment deposition and erosion experiments were conducted on a 5m (ring diameter) rotating annular flume located at NWRI in Burlington, Ontario. The flume consists of a circular channel (flume) and an annular cover plate (ring) that fits inside the channel (Figure 2.4). Flow is generated by lowering the ring inside the flume until it makes contact with the water surface and by rotating the ring and the channel in opposite directions. The maximum speeds of rotation for ring and flume are three revolutions per minute each for a maximum relative rotational speed of six revolutions per minute. This corresponds to a linear velocity of 1.6m/s in the flume (Krishnappan and Engel, 2004).

When the channel and ring of the flume are rotated in opposite directions at different speeds, the influence of secondary circulation cells is reduced. Peterson and Krishnappan (1994) found that the optimal speed ratio (α = rate of rotation of ring/rate of rotation of flume) is dependent on the water depth in the flume. They determined the optimal speed ratio between the ring and the flume to be 1.17 for a water depth of 0.12m. For both the plane bed and gravel bed experiments the water depth above the bed was maintained at 0.12m, therefore α value of 1.17 was used to determine the rotational speeds of the flume and ring.

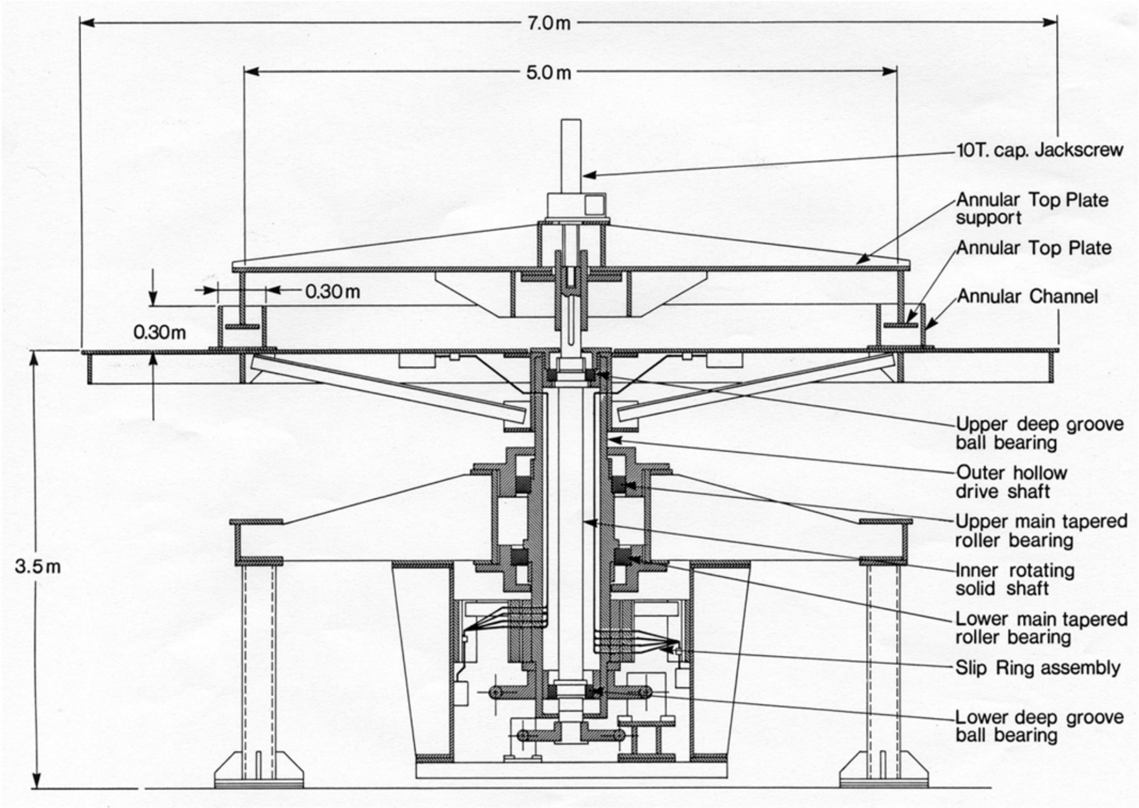


Figure 2.4 Cross-Sectional View of the Annular Rotating Flume Assembly (Krishnappan, 1993).

2.5 Flume experiments

The erosion and deposition experiments conducted in the annular flume are presented in Table 2.1

Table 2.1 Elbow River Cohesive Sediment Erosion and Deposition Experiments Conducted in the NWRI's Annular Flume.

Experiment	Run	Flume Speed (rpm)		Shear Stress (Pa)	Initial Concentration (ppm)	Consolidation period (hrs)
		Channel	Ring			
Deposition (plane bed)	1	1	1.17	0.123	289	0
Deposition (plane bed)	2	1	1.17	0.123	614	0
Deposition (plane bed)	3	1.33	1.56	0.212	593	0
Erosion (plane bed)	1	Variable - increasing		variable	614	113
Erosion (plane bed)	2	Variable - increasing		variable	614	39
Deposition (gravel bed)	1	1.33	1.56	0.48	181	0
Erosion (gravel bed)	1	Variable - increasing		variable	1.7	39

2.5.1 Plane Bed Deposition Experiments

Three deposition experiments using a plane bed condition were conducted. Experimental Runs 1 and 2 determined the steady state concentration at the same given bed shear stress with two different initial suspended sediment concentrations. These two experiments were conducted to determine whether the Elbow River fine sediments are cohesive. The third experiment compared steady state concentrations resulting from the same initial suspended sediment concentration and two different bed shear stress conditions. The deposition rates quantified from differing bed shear conditions were used to numerically determine the critical shear stress for deposition of the Elbow River cohesive sediments.

The flume was filled to a depth of 0.12m with decanted water from the Elbow River and rotated at high speed while the cohesive sediment slurry was added through a side port on the flume. A volume of water equal to the volume of slurry added was removed from the flume to maintain a constant water depth and surface contact with the lid. To ensure full and even mixing of the suspended sediments, the flume base and the lid were rotated at high speeds (2.5 rpm for the lid and 2 rpm for the flume, which corresponds to a bed shear stress of 0.6 Pa). The high speed operation of the flume was maintained for twenty minutes to produce a fully mixed suspended sediment concentration of 289 mg/L.

After a period of twenty minutes, the flume speed was reduced to a constant shear stress of 0.123 Pa. The flume was operated at this shear stress for a period of 320 minutes. During this time, 50mL water samples were collected every 5 minutes for the first 100 minutes and every 10 minutes for the next 230 minutes. Suspended solids concentrations were determined using a standard vacuum filtration method developed at NWRI (Environment Canada, 1988).

At the conclusion of the deposition experiment, the water and cohesive sediment mixture was retained within the flume for use in a second deposition experiment. Prior to initiating the second deposition experiment, the water and cohesive sediment mixture was agitated with a hand held blender to suspend all the cohesive sediments and to disaggregate any flocs. Additional cohesive sediment slurry was added to the flume to increase the suspended sediment concentration to 614mg/L. The flume was operated at a high rate of speed (2.5 rpm for the lid and 2 rpm for the flume, corresponding to a bed shear stress of 0.6 Pa) for 20 minutes and samples were collected every five minutes to determine the initial starting concentration. The second experiment followed the methods of the first, for a total run time of 230 minutes with a constant shear stress of 0.123Pa.

The cohesive sediment mixture (614mg/L) was used in the third experiment and the constant shear stress was increased to 0.212Pa. The suspended sediment concentration was thoroughly mixed prior to operating the flume with a hand held blender. The flume was then operated at a high rate of speed for 20 minutes. The flume speed was reduced to maintain a constant shear stress of 0.212Pa for a total experiment run time of 230 minutes.

2.5.2 Erosion Experiments

The critical shear stress for erosion can vary for cohesive sediments collected from rivers in different geological and hydrological settings but it can also be influenced by other factors such as consolidation time (Krishnappan and Engel, 1994; Milburn and Krishnappan, 2003). Accordingly, the critical bed shear stress and overall bed erosion characteristics of cohesive sediment from the Elbow River were measured for two consolidation periods (39 hours and 113 hours).

Cohesive sediment and water from the Elbow River used in the deposition experiments was retained in the flume for the erosion experiments. The cohesive sediments and water were thoroughly mixed with an electric hand mixer to disaggregate flocs. The flume was operated at a high speed, corresponding to a bed shear stress of 0.6Pa, for 20 minutes to ensure a homogenous suspended sediment mixture. After 20 minutes of mixing, the rotational speed of the flume was reduced gradually over a 5 minute period until coming to a complete stop. This routine was followed for two consolidation periods of 39 and 113 hours in which the bed was left undisturbed. During the consolidation period, solids settled from the water column to the bottom of the flume, creating a cohesive sediment bed under a low shear environment. The duration of the consolidation period was intended to limit the potential for biofilm growth and was based on knowledge gained from previous experiments conducted at the NWRI flume, specifically the length of time required for biofilms to form on the bed surface influencing the critical shear stress (Krishnappan and Engel, 1994; Stone and Krishnappan, 1997, 2002, 2003; Milburn and Krishnappan, 2003). No chemical or biological analysis of the sediments or water was conducted in this research to determine the effect of biofilm growth on bed stability. Additionally, no microscopic imaging to detect biofilm growth or genetic testing was conducted to determine the nature of the biofilms.

For each erosion experiment (consolidation periods 39 and 113 hours), the flume was started from rest and the rotational speed was increased in time increments of 60 minutes. Time steps were based on standard time steps used in previous plane bed cohesive sediment erosion experiments in the annular flume as were the corresponding shear stress steps (Krishnappan and Engel, 1994; Stone and Krishnappan, 1997, 2002, 2003; Milburn and Krishnappan, 2003). Use of the same methodological protocols allowed direct comparisons to be made with the results of other comparable studies. The time steps used and the corresponding flume rotational speed and correlated bed shear stress are listed in Table 2.2.

Table 2.2 Time and Bed Shear Stress Steps and Corresponding Ring and Flume Speeds Used in the Plane Bed Erosion Experiments

Time Step (minutes)	Flume Speed (rpm)	Ring Speed (rpm)	Shear Stress (Pa)
0 to 60	0.67	0.78	0.058
70 to 120	0.83	0.97	0.088
130 to 180	1	1.17	0.123
190 to 240	1.17	1.36	0.165
250 to 300	1.33	1.56	0.212
310 to 360	1.5	1.75	0.265
370 to 420	1.67	1.95	0.325

A 50 mL water sample was collected from the flume sampling port every 10 minutes for suspended solids analysis using a standard gravimetric filtration method (Environment Canada, 1988). Both erosion experiments were run for a total of 420 minutes. After completion of the erosion experiments, the flume was left stationary for 5 days to allow for full settling of the all suspended sediments to the bottom of the flume. Thereafter the water was decanted from the flume and both water and sediment were retained for the entrapment experiments.

2.5.3 Entrapment Experiments - Deposition

Washed gravel was used to construct a 0.08m thick bed in the flume. A jig cut from 5mm hard plastic panel board was used to ensure a consistent depth and flat gravel bed surface was maintained in the flume. The jig fit the flume sides tightly and was flush with the top of the trough when the gravel bed depth was 0.08m. The flume was filled with Elbow River water to a depth of 0.12m above the gravel bed. This depth was consistent with the water depth in the plane bed erosion and deposition experiments. Total depth for the gravel and water was 0.2m.

A cohesive sediment slurry was added to the flume over a 20 minute period during which time the flume was operated at high speed to ensure thorough mixing of the cohesive sediments and flume water. After the water and sediment was mixed for 20 minutes at high speed, the flume and the ring speeds were reduced to 1.3 and 1.6 rpm respectively, corresponding to a bed shear stress of 0.48Pa. The PHOENICS 3D hydrodynamic model was used to calculate the bed shear stress for the gravel bed. A full description of the model is provided in Rosten and Spalding (1984). The shear stress was maintained at 0.48Pa for the duration of experiment. Water samples for suspended sediment measurements were collected every 5 minutes for the first 100 minutes and every 10 minutes for the following 230 minutes. The entrapment experiment was run for a total of 330 minutes.

2.5.4 Entrapment Experiment – Erosion

To allow for comparison between the plane bed and gravel bed experiments, the same basic mythological approach was applied to both sets of experiments. A 39 hour consolidation period was used to minimize the opportunity for biofilm growth and bed stabilization as demonstrated in the plane bed erosion experiments. Flume speed was increased in stepwise time increments of 60 minutes. The gravel bed erosion experiment was extended by two additional steps compared to the plane bed experiments to bring the flume close to its maximum operation speed. The two additional steps were included to test the response of fine sediment release from the bed under the maximum flow velocities produced within the flume. The experiment was run for a total of 540 minutes. A summary of the time steps, rotation flume speeds and corresponding bed shear stress is provided in Table 2.3.

Table 2.3 Time and Bed Shear Stress Steps and Corresponding Ring and Flume Speeds Used in the Gravel Bed Erosion Experiments

Time Step	Flume Speed (rpm)	Ring Speed (rpm)	Shear Stress (Pa)
0 to 60	0.67	0.78	0.125
70 to 120	0.83	0.97	0.2
130 to 180	1	1.17	0.29
190 to 240	1.17	1.36	0.39
250 to 300	1.33	1.56	0.48
310 to 360	1.5	1.75	0.64
370 to 420	1.67	1.95	0.78
430 to 500	1.83	2.14	0.93
510 to 540	2	2.33	1.11

2.6 Bed Sediment Size Distribution

Between 20 to 25kg of gravel was removed from the flume for particle size analysis. The sample was divided into four smaller subsets for sieving. The sieve intervals were on a full Phi sizing from -2 to -4 and half Phi intervals ranging from -4 to -6 with an additional -4.75 sieve added between -4.5 and -5. Each subsample was placed in the sieve stack and agitated on an automated shaker for fifteen minutes. The contents of each sieve were weighed and the mass of each individual Phi size from the subsamples were aggregated to determine the total weight of each Phi scale (Bunte and Abt, 2001).

The size distribution of the point bar core samples was determined following the procedure described above. Samples were air dried prior to sieving. For the core samples the sieve stack was expanded to cover a Phi range from -5.5 to 4. Each core was analyzed as a single sample. An average of the three core samples was used to establish the sediment size distribution of the top 0.08m of the Elbow River point bar.

2.7 Cohesive Sediment Size Distribution

The particle size distributions of Elbow River cohesive sediment were analyzed by using laser diffraction (a Malverin Masterziser 2000) in the Geography Department at Wilfrid Laurier University.

2.7.1 Estimating in situ fine sediment storage in gravel beds

The mass of cohesive sediment stored within the gravel bed of the flume was estimated using the method of Lambert and Walling (1988). After the completion of the gravel bed erosion experiment, two cells ($0.12m^2$ and $0.11m^2$) were isolated within the flume using hard plastic panels cut to fit the sides and bottom of the flume tightly. The bed was mechanically agitated with a steel rod within the cells. While agitating the water, 50ml samples were collected from the cells for a total of three from Cell 1 and four from Cell 2. The suspended sediment concentration within the cells was determined following the Environment Canada (1988) protocol. The mass of the cohesive sediment stored within the bed was calculated by correlating the mass of suspended sediment to the volume of water and gravel within the sampling cells.

2.8 Settling Velocity

Settling velocity of cohesive sediment from the Elbow River was calculated following approach described by Krishnappan (2007). This method uses a size-dependent density relationship (equation 9) to correct for decreasing density with increasing floc size.

$$\rho_s - \rho = \rho_p^{-bD^c} \qquad [13]$$

where ρ is the density of water and ρ_p is the density of the parent material forming the floc, D is the diameter of the floc, and b and c are empirical coefficients. Accounting for the size-density relationship, the expression for determining floc settling velocity is:

$$w_k = (1.65/18.00)^{-bD_k^c g D_k^{2/v}} \qquad [14]$$

where w_k is the settling velocity of the kth fraction, D_k is the size of the sediment floc, the parameters b and c are empirical coefficients that are treated as calibration parameters and ν is the kinematic viscosity of the fluid (Krishnappan, 2007). The size of the flocs (D_k) was determined using laser diffraction.

To determine the settling velocity, cohesive sediment from the Elbow River was added to the flume which was rotated at high speed for twenty minutes. The flume speed was then reduced in 60 minute time steps until the flume was at rest. Sampling was conducted every 10 minutes to determine suspended sediment concentrations and grain size.

Sampling continued after the flume had come to rest to determine the deposition at zero shear stress.

The settling and flocculation model presented above were used to determine the relationship between the floc size, floc density and settling velocity by matching the measured deposition pattern with the predicted deposition pattern from the model by adjusting the empirical coefficients. The settling velocity experiments were completed for the Glenmore Reservoir Erosion Study and the settling velocity data were provided by Dr. Krishnappan.

Chapter 3. Results

3.1 Deposition and Erosion with a Plane Bed

3.1.1 Deposition of Cohesive Sediment on a Plane Bed

The concentration of suspended sediments decreased rapidly during the first 10 minutes of the two deposition runs at a shear stress of 0.123Pa (Figure 3.1), reaching a steady state condition after approximately 60 minutes. The steady state concentration for the first run (initial concentration of 289mg/L) was 14mg/L, corresponding to a 95% deposition rate, and for the second run (initial concentration of 614mg/L) was 35mg/L, representing a 94% deposition rate.

Suspended sediment concentrations decreased rapidly during the first 25 minutes of the third deposition experiment conducted at a shear stress of 0.212Pa. The deposition rate was not as rapid as observed in the lower shear stress (0.123Pa) experiments (Figure 3.2). The steady state concentration at a shear stress of 0.212Pa was 258mg/L, represented a deposition rate of 56%. The deposition rates for the shear stress conditions at 0.123Pa and 0.212Pa are presented in Figure 3.2, showing a difference of 223mg/L between the steady state concentrations, with the higher shear stress (0.212Pa) resulting in a higher steady state concentration. The deposition experiments show that 95% of the suspended sediments were deposited at 0.123Pa. If the bed shear stress was reduced slightly below this level, then all of the suspended materials in the water column could theoretically deposit onto the bed.

Accordingly, this shear stress condition is operationally defined as the critical shear stress for deposition (Stone and Krishnappan, 1997).

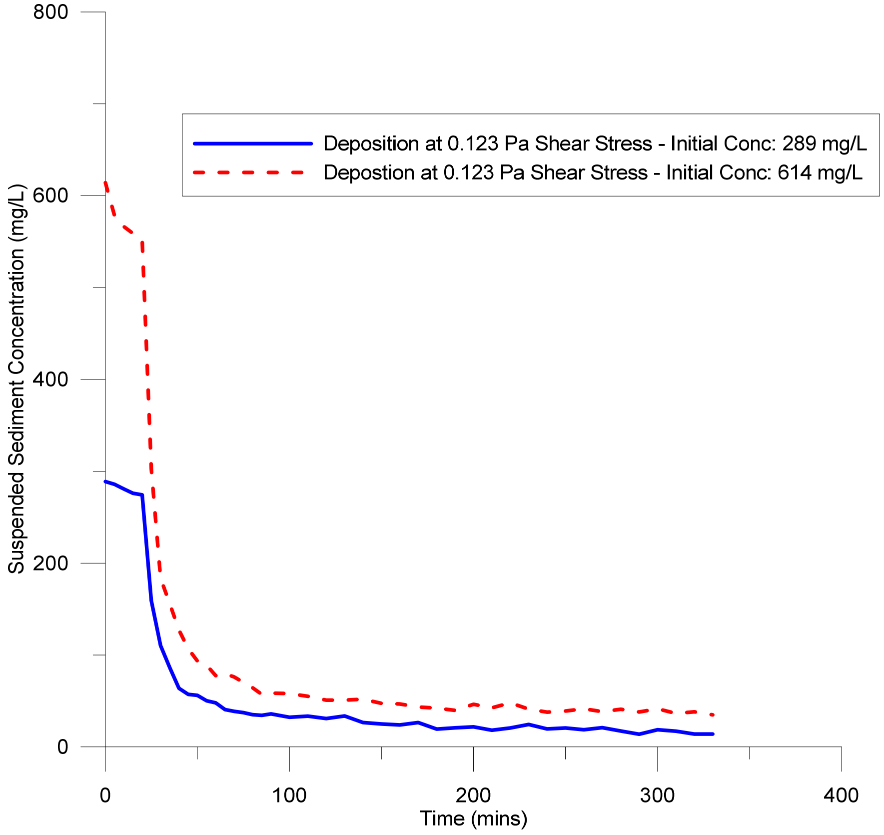


Figure 3.1 Plane Bed Deposition Experiments at Constant Shear Stress of 0.123Pa with Initial Sediment Concentrations of 289mg/L and 614mg/L.

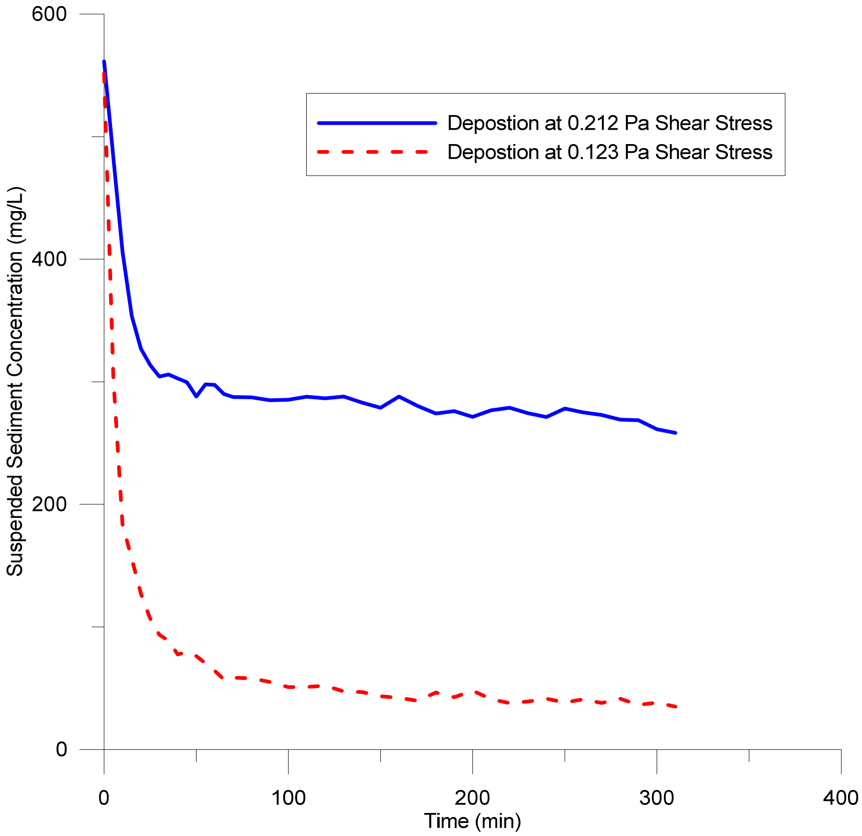


Figure 3.2 Plane Bed Deposition Experiments with Initial Sediment Concentrations of 614mg/L and with a Bed Shear Stress of 0.123Pa and 0.212Pa

3.1.2 Erosion of Cohesive Sediment from a Plane Bed

Two erosion experiments were conducted in the flume to determine the critical bed shear stress (τ_c) of the Elbow River cohesive sediments. Erosion experiments were conducted on bed sediments with two consolidation periods (39 hours and 133 hours) and results of the experiments are presented in Figure 3.3.

The critical shear stress for bed erosion was 0.212Pa for the 39 hour consolidation period, with a final suspended sediment concentration of 357mg/L measured at a shear stress of 0.325Pa. The critical bed shear stress for the 133 hour consolidation period was 0.212Pa and a final suspended sediment concentration of 214.1mg/L measured at a shear stress of

0.325Pa. Suspended sediment concentrations show a slight increase for the 39 hour consolidation bed beginning at 0.165Pa indicating that initial bed movement may have been initiated at this shear stress. Bed failure and erosion occurred at 0.212Pa for both consolidation periods as indicated by the rapid increase in suspended sediment concentration (Figure 3.3). The suspended sediment concentration was higher after bed mobilization for the 39 hour consolidation period as was the overall bed erosion response. This was evident as the cumulative bed erosion, which is defined in this study as suspended sediment concentration measured at the end of the final shear stress step, was higher for the 39 hour consolidation period at 357mg/L compared to 214mg/L for 113 hour consolidation period. This corresponds to approximately 40% higher final suspended sediment concentration for the shorter consolidation period.

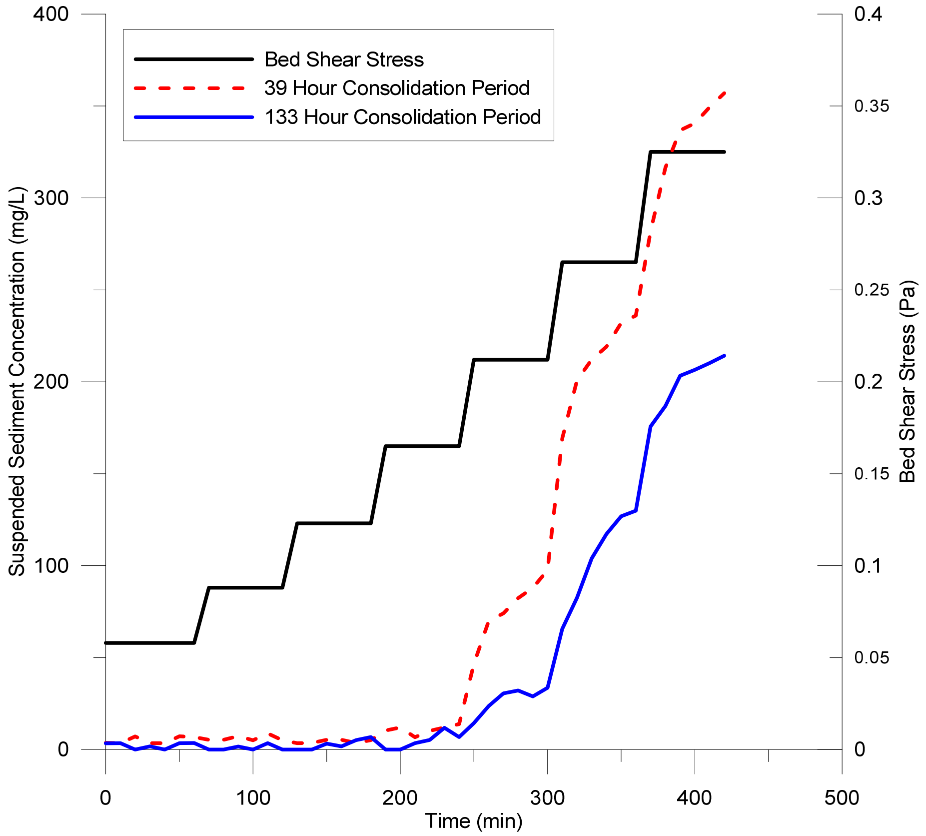


Figure 3.3 Cohesive Sediment Bed Erosion for 39 Hour and 113 Hour Consolidation Periods using a Step-Wise Increasing Shear Stress.

3.2 Deposition and Erosion with a Coarse Bed

3.2.1 Entrapment Experiment - Deposition

The results of deposition experiments in the flume with coarse gravel and plane beds at the same rotational speed (1.33 rpm) are presented in Figure 3.4. Suspended sediments in the water column rapidly declined during the initial 15 minutes of the experiment after which a steady state concentration of 11.86mg/L was measured. Approximately 93% of the fine sediment was deposited either on or into the coarse bed compared to 56% onto the plane bed.

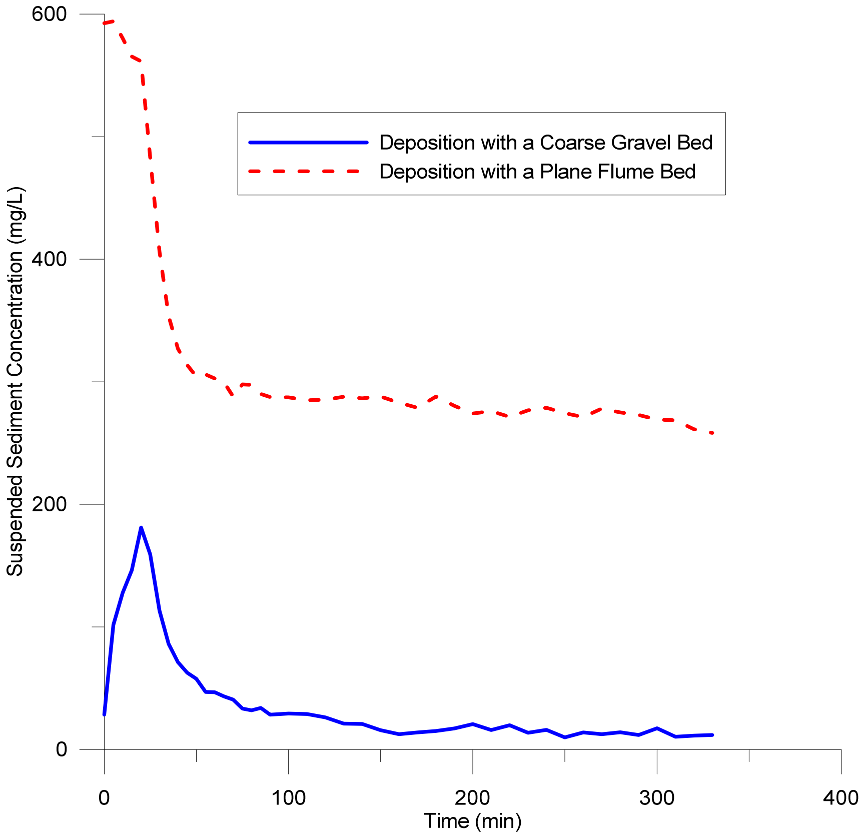


Figure 3.4 Sediment Deposition Comparing Coarse Gravel and Plane Bed Flume Conditions with the Same Mass of Cohesive Sediment Injected into the Flume for Both Experiments and Run at the Same Constant Flume Speed.

3.2.2 Entrapment Experiment - Erosion

The flume was operated with step wise increases in shear stress to determine if sediment entrapped within the gravel bed during the deposition experiment could be remobilized. Remobilization of fine sediment from the coarse gravel bed did not occur for any of the shear stress conditions examined during this run (Figure 3.5). Mobilization of the coarse bed is required to release the fine sediments to the water column (Diplas, 1947; Einsten, 1968; Schalchli, 1992). However, because the flume could not generate sufficient flow velocity to exceed the critical shear stress of the gravel bed, remobilization of the fine sediment was not observed.

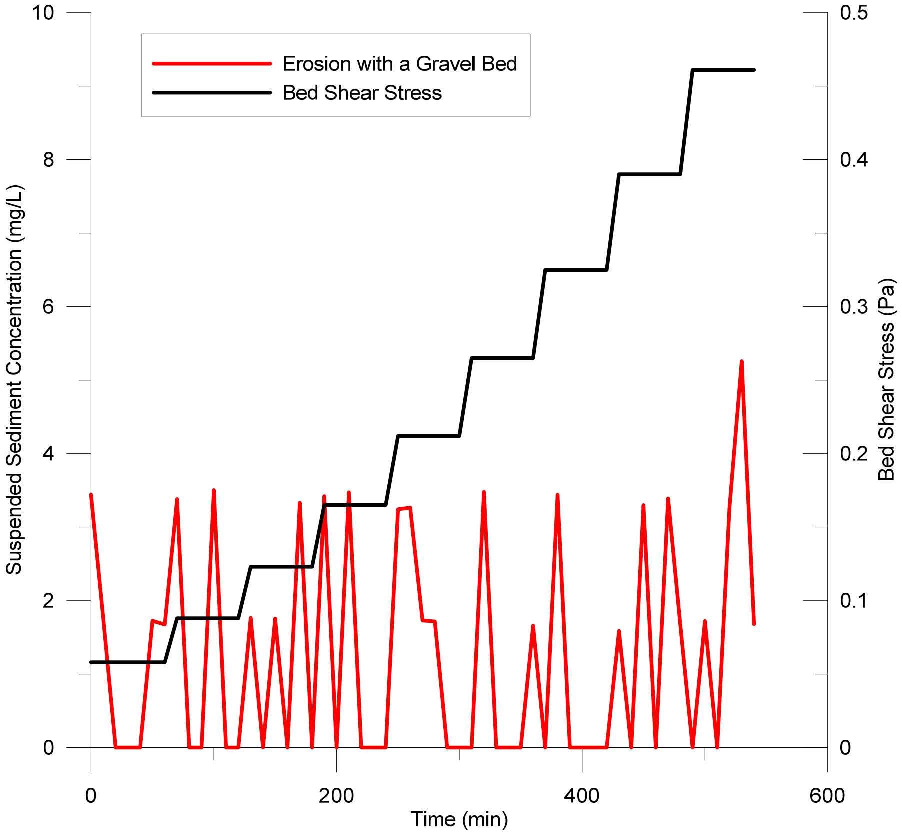


Figure 3.5 Erosion Experiment using a Coarse Gravel Bed. Results Show a Pulse of Suspended Sediment Concentrations Followed by Zero Suspended Sediment Concentration.

3.3 Cohesive Sediment and Bed Substrate Distribution

3.3.1 Mass of Fine Sediment Stored in the Flume Gravel Bed Analysis

The mass of fine sediments entrapped within the gravel bed was calculated using the method of Lambert and Walling (1988). Two isolation cells were created in the flume and three 50ml samples were collected from each cell. Suspended sediment concentrations were used in conjunction with the volume of water and gravel within the sample cells to calculate the mass of cohesive sediment trapped within the gravel bed (Table 3.1). Water depth above the gravel bed at the time of the analysis was 0.065m and the 0.08m gravel bed had not been disturbed prior to sampling. Combined the two sampling cells covered approximately 3% of the flume's gravel bed surface area.

Averaging the results of the two bed agitation sampling cells, the mass of cohesive sediment trapped by coarse gravel was 598.5g (standard deviation 15.9). The initial concentration of cohesive sediment added to the flume during the plane bed deposition experiments was 630g. The mass of cohesive sediment determined to be stored in the gravel through the bed agitation method accounted for 95% of the initial mass of cohesive sediment added to flume.

Table 3.1 Mass of Sediment Entrapped in the Gravel Bed in the Flume Calculated using Suspended Sediment Concentrations Resulting from Mechanical Bed Agitation in Conjunction with the Volume of Water and Gravel in the Sampling Cell.

Sampling Cell 1				
Filter #	**Suspended Sediment Concentration (mg/L)**	**Mass of Sediment in Gravel in Sampling Cell (g)**	**Mass of Sediment in Cubic Unit of Gravel (g/m^3)**	**Mass of Sediment in Flume (g)**
56	1150.00	8.87	934.38	639.11
57	1148.40	8.85	933.08	638.23
58	992.68	7.65	806.55	551.68
Average	1097.03	8.46	891.33	609.67
Standard Deviation	90.37	0.70	73.43	50.22
Sampling Cell 2				
59	1054.94	7.56	857.14	586.28
60	1077.11	7.26	823.87	563.52
51	1080.68	7.72	875.15	598.60
52	1013.99	7.74	878.05	600.59
Average	1056.68	7.57	858.55	587.25
Standard Deviation	30.65	0.22	24.91	17.04

3.3.2 Size Distribution of Cohesive Sediment, Point Bar Sediment and Sieved Coarse Gravel

Size distribution for the cohesive sediment, gravel bed and the Elbow River point bar core samples was determined and are presented in Table 3.2. The grain size data are expressed as the D_{16}, D_{50} and D_{95}.

Table 3.2 Size Distribution (D_{16}, D_{50} and D_{95}) of the Elbow River Point Bar, Flume Gravel Bed and Cohesive Sediment.

Size Fraction	Point Bar (mm)	Flume Gravel (mm)	Cohesive Sediments (mm)
D_{16}	4.4	12	0.003
D_{50}	17	21	0.017
D_{95}	56	40	0.102

The size distributions of cohesive sediments in three depositional environments are presented in Figure 3.6. Elbow River sediments were filtered prior to preparing the slurry for flume experiments to ensure the constituent particles were all < 64µm. The D_{50} of cohesive sediment was 17µm and D_{95} was 102.95µm. Particles > 64µm may result from either sediment aggregation or floc formation within the slurry prior to analysis.

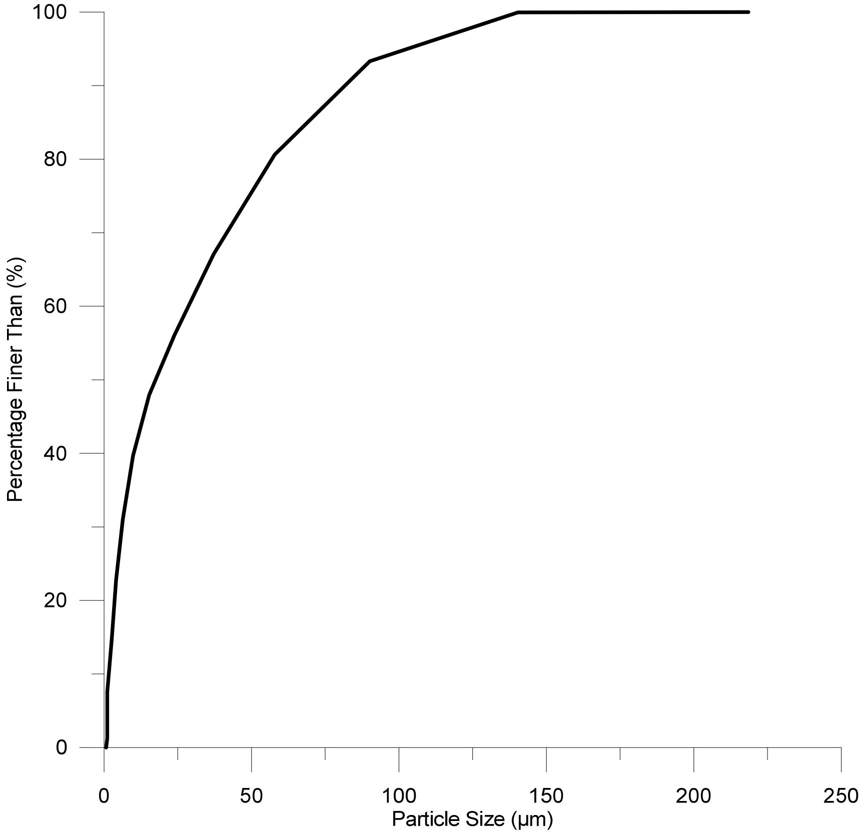


Figure 3.6 Percent Finer by Volume of the Elbow River Cohesive Sediments Determined through Laser Diffraction.

The sediment size distribution of the coarse gravel bed used in the flume is presented in Figure 3.7.

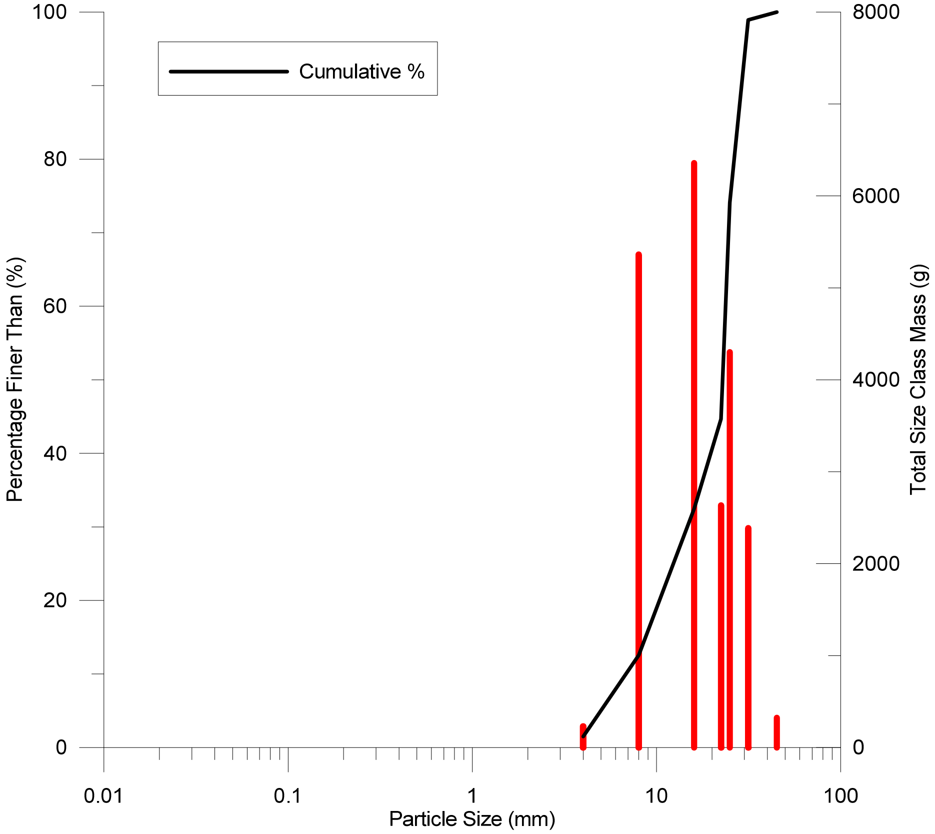


Figure 3.7 Size Distribution and Total Size Class Mass for Flume Gravel Bed.

The size of bed materials in the point bar deposit ranged from coarse to very coarse gravels. The majority of the gravel used in the flume experiments ranged from 15 to 30mm in diameter. The sediment size distribution from the point bar core samples at the Elbow River study site is presented on Figure 3.8.

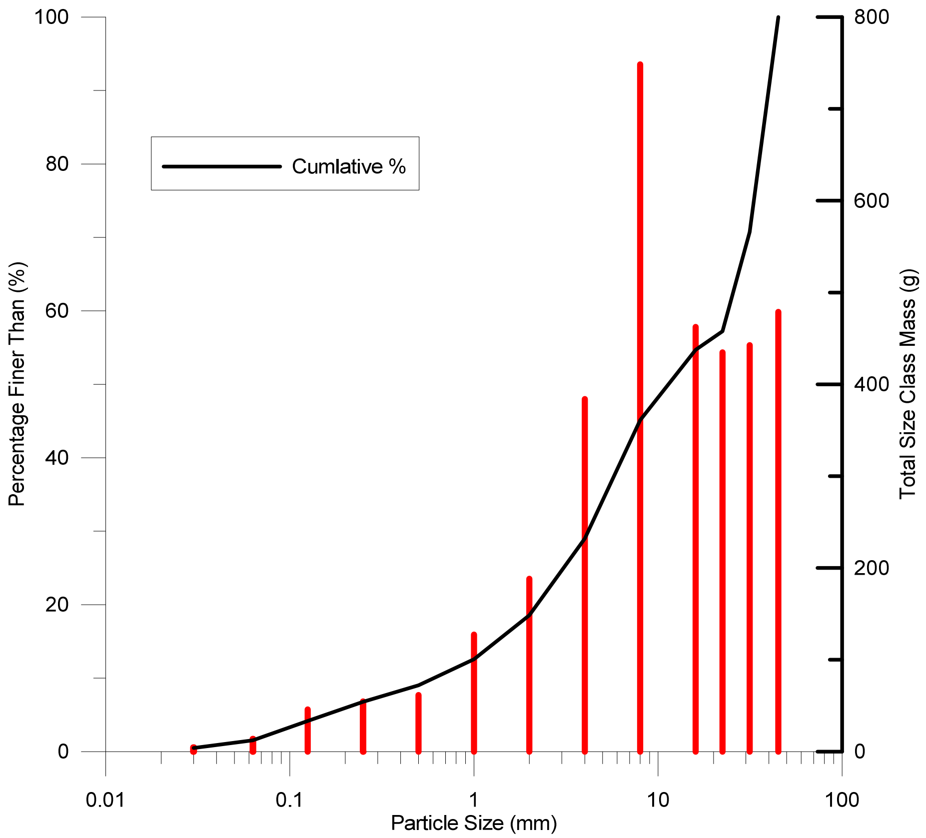


Figure 3.8 Size Distribution and Total Size Class Mass for the Elbow River Point Bar.

The Elbow River point bar had a much broader size distribution compared to the gravel bed used in the flume experiments. This demonstrates the effect of washing and sieving the Elbow River substrates for use within the flume. The cohesive sediments (<64µm) represented 0.53% of the sediment mass in the sample. The D_{50} of 17mm is classified as coarse gravel.

3.3.3 Density and Settling Velocity of Cohesive Sediment

The settling velocity and density of Elbow River cohesive sediment as function of particle size is presented in Figure 3.9.

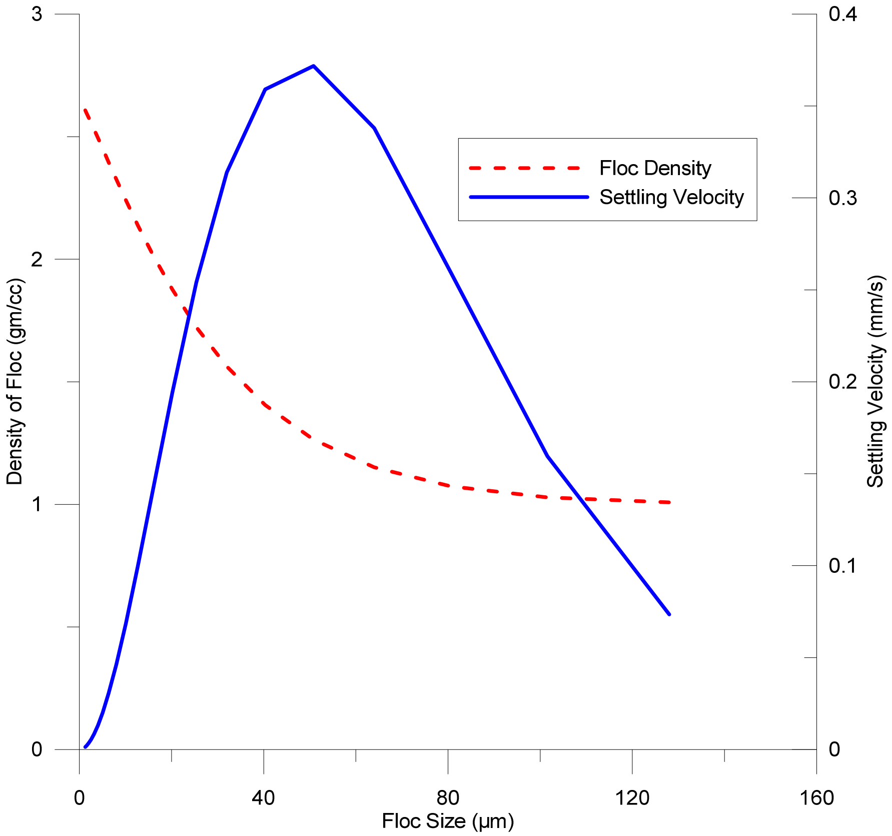


Figure 3.9 Elbow River Cohesive Sediment Density and Settling Velocity of Flocs

The data show that floc density decreased with floc size. Using the size/density relationship (Figure 3.9) and the particle analysis completed at Wilfrid Laurier University it was determined that the density of the constituent parent particles is 2.61gm/cc and approximately 2.0gm/cc for the D_{50} of 17.17µm. Particle density approached that of water (1gm/cc) for particles greater than 100µm. A maximum settling velocity of 0.37mm/s occurred for 50µm flocs but decreased to 0.07mm/s for 128µm flocs.

Chapter 4. Discussion

4.1 Introduction

Cohesive sediment transport and storage are governed by a complex set of physical, chemical and biological processes in rivers. The transport characteristics of cohesive sediments are fundamentally different than non-cohesive sediments and are unique for each aquatic environment (Krishnappan and Engel, 2006). Accordingly, their transport characteristics must be determined experimentally (Krishnappan and Engel, 1994). In this chapter, the results of the flume study are discussed and interpreted in the context of previous research to highlight the uniqueness of the work.

4.2 Cohesive Sediment Deposition on a Plane Bed

The first two deposition experiments conducted at a constant shear stress of 0.123Pa and differing initial suspended sediment concentration demonstrated that the steady state concentration of Elbow River sediment is dependent on the initial suspended sediment concentration at the same bed shear stress. This observation is consistent with Partheniades (1968) who demonstrated that the steady state concentration is a function of the rate of aggregation and disaggregation of flocs on a bed and that the steady state concentration of cohesive sediment was dependent on the initial concentration for a given bed shear stress. The results of the two deposition experiments with different initial sediment concentrations and the same shear stress conditions (0.123Pa) were normalized (expressed as a percent fraction of sediment remaining in suspension from the initial concentration) and plotted (Figure 4.1). Both deposition curves are in good agreement and show that the percent of steady state sediment concentration to the initial sediment concentration was the same for the two experiments.

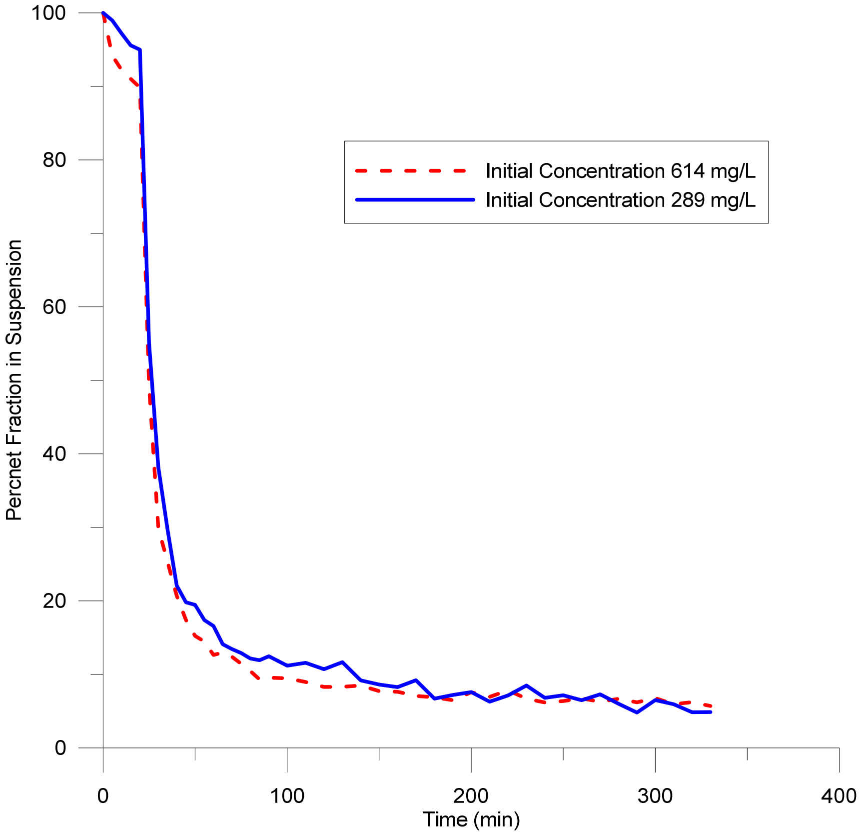


Figure 4.1 Normalized Deposition Plots Showing Percent Fraction of Suspended Sediment in Suspension at a Constant Bed Shear Stress of 0.123 Pa with Initial Sediment Concentrations of 614 mg/L and 289 mg/L.

Accordingly, steady state sediment concentrations were shown to be a function of both shear stress condition and the initial suspended sediment concentration. Milburn and Krishnappan (2003, pg. 134) state, “cohesive sediments form flocs and that only strong flocs capable of withstanding high shear stress near the bed are deposited while weaker flocs break up at the region of high shear and remain in suspension. Only a certain fraction of sediment can form stronger flocs and the amount of sediment remaining in suspension becomes a function of the amount of sediment in the initial suspension.”

To provide a quantitative estimate of the amount of sediment deposited over a range of steady state concentrations measured under differing bed shear stress conditions, two depositional experiments with initial suspended sediment concentrations of 614mg/L and shear stress conditions of 0.212Pa and 0.123Pa were compared. The resulting steady concentrations can be expressed as a fraction of the initial sediment concentration with a value of one indicating complete deposition (Milburn and Krishnappan, 2003). The critical stress for deposition is than extrapolated using a fitted power law relationship between the fraction deposited and bed shear stress (Milburn and Krishnappan, 2003). The fractions of Elbow River cohesive sediment deposited were 0.57 and 0.94 for shear stress of 0.123Pa and 0.212Pa, respectively. Using the fitted power law relationship the critical shear stress for deposition for the Elbow River cohesive sediments is 0.115Pa. Previous annular flume studies show the critical shear stress for deposition for other Canadian rivers to be approximately half (0.56Pa) the 0.115Pa identified for the Elbow River cohesive sediments (Table 4.1). These differences are likely related to the distinct physical, chemical, and biological characteristics of the parent materials and river bodies.

Table 4.1 Critical Shear Stress for Deposition of Cohesive Sediments from Various Canadian Rivers.

Study	River	Critical Shear Stress for Deposition (Pa)
Millburn and Krishnappan (2003)	Hay River, NWT	0.08
Stone and Krishnappan (1997)	Tile drains in the headwaters of the Thames River, Ontario	0.056
Krishnappan and Engel (1994)	Fraser River, BC	0.056
Current Study	Elbow River, Alberta	0.115

4.3 Cohesive Sediment Erosion

The critical shear stress for the deposition of cohesive sediment is lower than for erosion (Stone and Krishnappan, 1997; Milburn and Krishnappan, 2003; Krishnappan, 2007). This characteristic is unique to cohesive sediments and therefore both the shear stress for deposition and erosion must be derived experimentally (Krishnappan, 2007). The critical shear stress for erosion of the Elbow River sediment was 0.212Pa for materials deposited during the 39 and 113 hour consolidation periods. The critical shear stress for erosion of the Elbow River sediment was approximately two times higher than the critical shear stress for deposition (0.115Pa), which is consistent with results observed in other studies (Stone and Krishnappan, 1997; Milburn and Krishnappan, 2003).

Due to differences in the geochemical, mineralogical and biological composition of materials found in different geographical locations cohesive sediment can have different transport properties. The critical shear stress for erosion for Elbow River cohesive sediments is higher than critical shear stresses reported for other Canadian rivers (Table 4.2). The critical shear stress for cohesive sediments in Canadian rivers ranged from 0.1 to 0.2Pa (Table 4.2). This demonstrates that while the methods used in this study were appropriate for determining the critical shear stress for erosion, the results increased the range of critical shear stress experimentally derived for a variety of Canadian rivers, showing that discrete values determined for one river are not directly transferable to other rivers.

Table 4.2 Critical Shear Stress for Erosion of Cohesive Sediments from Various Canadian Rivers.

Study	River	Consolidation Period (Hours)	Critical Shear Stress for Erosion (Pa)
Milburn and Krishnappan (2003)	Hay River	24	0.123
Stone and Krishnappan (1997)	Tile Drains in Southern Ontario	114	0.121
Krishnappan and Engel (1994)	Fraser River	164	0.121
Droppo (2009)	South Nation River	48	0.14
Stone et al. (2010)	Castle River	48	0.12
Stone et al. (2010)	Lynx River	48	0.105
Current Study	Elbow River	39 and 113	0.212

Bed consolidation influences the critical shear stress for erosion by increasing critical shear stress with increased consolidation period (Krishnappan and Engel, 1994; Droppo and Amos, 2001; Milburn and Krishnappan, 2003). In this study, the influence of consolidation period on bed erosion and bed mobility was investigated. While the consolidation period did not show the same influence on the critical shear stress for erosion for the Elbow River sediments as described in the literature for other rivers, it did influence overall bed mobility. Total bed mobility is defined as the final suspended sediment concentration measured at the maximum shear (0.325Pa). Approximately 67% greater bed mobilization was observed with a 39 hour compared to 113 hour consolidation period. Factors contributing to bed stability associated with consolidation period could include: 1) the formation and strengthening of ionic bonding between the cohesive constituent particles over time (Metha, 1989); 2) self-weighting and compression (Droppo and Amos, 2001); and/or, 3) the development of biofilms and EPS between particles (Stone *et al.*, 2008; Droppo, 2009). Bed consolidation can influence the critical shear stress of deposited cohesive sediments but also influences the overall mobility of the bed once the bed critical shear stress has been exceeded. The mechanism responsible for overall bed erosion associated with consolidation time was not investigated in this study but is an area requiring further research.

4.4 Coarse Bed Deposition Experiments

Cohesive sediment transport in rivers is complex and requires a mechanistic understanding of entrapment in coarse gravel beds (Krishnappan, 2007). This study quantified the effect of a gravel bed on the transport of fine sediment. Results of the entrapment experiments were used to determine an entrapment coefficient (Krishnappan and Engel, 2006) which was compared to data reported in published literature.

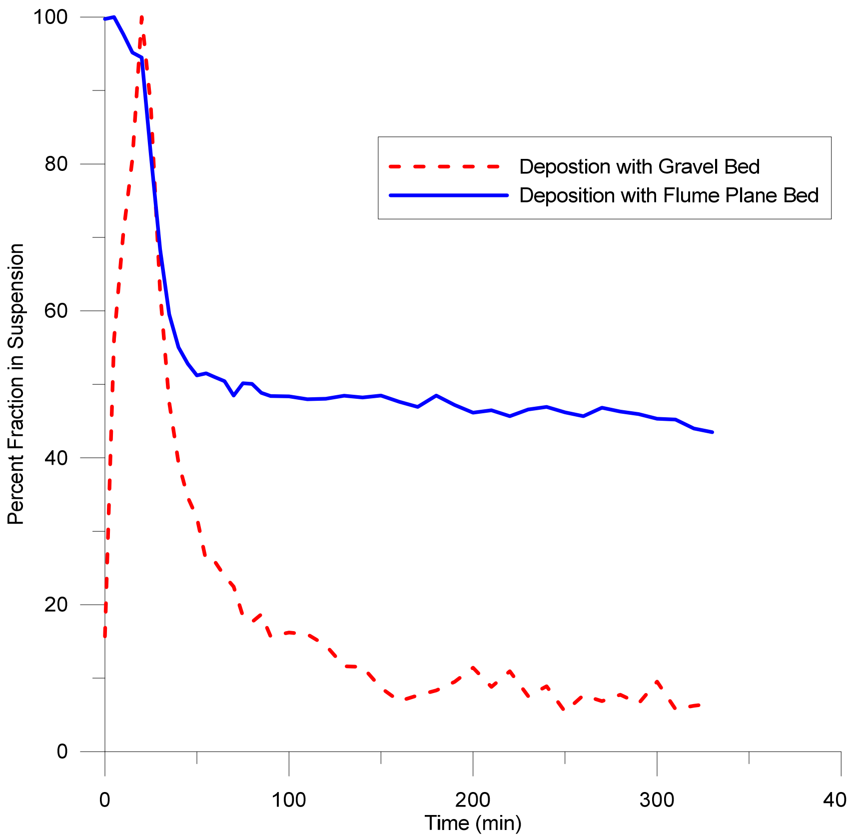


Figure 4.2 Normalized Deposition Plots of the Percent Fraction of Suspended Sediment in Suspension for Plane and Gravel Bed Condition at the Same Flume Speed.

To determine the role and influence of the gravel bed on the deposition of cohesive sediments, the results of the plane bed deposition experiments were compared to the gravel bed deposition experiments. Comparisons were made between plane and coarse bed deposition experiments run at the same flume speed (refer to Figure 3.4). The results of the deposition experiments were normalized to initial concentrations (Figure 4.2) and show greater suspended sediment removal from the water column with a gravel bed than for plane bed conditions. The gravel bed reduced the steady state sediment concentration by 83%

compared to plane bed conditions, showing the gravel bed enhanced cohesive sediment deposition. Similarly, Krishnappan (2007) found greater removal of fine sediment from the water column with gravel bed than plane bed conditions.

Numerous studies have demonstrated that gravel beds trap fine sediments suspended in the water column (Diplas, 1947; Einstein 1968; Packman and Salehin 2003; Packman *et al*., 2004; Krishnappan and Engel, 2006). The results of this study are consistent with these previous studies, which found the removal of suspended sediments from the water column occurred not only by settling on top of the gravel bed but also directly within the interstitial spaces of the gravel matrix.

Turbulence induced by gravel bed roughness can promote advective pumping of surface water into the bed (Nagaoka and Ohgaki, 1990; Packman and Salehin, 2003). As surface water is pumped into the bed, fine sediments in suspension are transported and deposited within the gravel. Downward movement of particles into the gravel bed was observed though a window in the flume during the deposition experiment in this research. Fine sediments could only be present in the pore water due to an exchange with surface water, indicating a coupling of the surface and pore water flow by means of a pumping mechanism. Horizontal and vertical distribution of fine sediments within the gravel bed was confirmed by removing the gravel in layers, showing cohesive sediments were evenly distributed throughout the entire gravel bed profile. These two observations provide good evidence that cohesive sediments were being transported into and becoming entrapped within the gravel bed during the deposition experiment.

A greater proportion of cohesive sediments were maintained in suspension during plane bed erosion experiments under the higher bed shear stress condition. The steady state concentration for the plane bed and gravel bed deposition experiments with differing bed shear stress conditions were compared to determine if a similar trend existed. At a flume speed of 1.33 rpm, the shear stress for plane bed and coarse bed experiments were calculated using the PHOENICS model to be 0.212Pa and 0.48Pa, respectively. The higher bed shear stress associated with the gravel bed did not result in a higher steady state suspended sediment concentration (Figure 4.2), with the steady state sediment concentration for the gravel bed 83% lower than for plane bed conditions despite a 126% increase in bed shear stress. This result is an inverse of the plane bed deposition experiment results.

The introduction of gravel to the flume reduced the suspended sediment concentration despite a higher applied bed shear stress. Accordingly, the data highlights the role gravel has on suspended sediment concentrations within the water column and suggests this effect may have a greater influence on suspended sediment concentration than bed shear stress. This reinforces the importance of factoring in the role gravel entrapment when modelling cohesive sediment transport in rivers, supporting the inclusion of an entrapment coefficient within cohesive sediment transport models such as the one suggested by Krishnappan and Engel (2006).

4.5 Cohesive Sediment Mobilization from a Gravel Bed

Understanding the factors controlling the entrapment and release of cohesive sediment from gravel beds is required to quantify and model the transport of cohesive sediments in rivers. Previous studies have shown that fine sediments remain entrapped in a gravel bed until a shear stress sufficient to mobilize the gravel armor layer is exceeded (Diplas, 1947; Enstein, 1968; Schalchli, 1992; Rehg *et al.*, 2005; Krishnappan and Engel, 2006). To better understand the role gravel beds play in cohesive sediment storage, this study considered two aspects of cohesive sediment mobility from a gravel bed: 1) the potential for mobility of entrapped cohesive sediment from a stable gravel bed; and, 2) mobility from a disturbed bed.

Cohesive sediments can enter a stable gravel bed through pore water exchange (Nagaoka and Ohgaki, 1990), conversely, it is then logical that sediments can also be mobilized from the bed through pore water exchange. To determine if cohesive sediments could be mobilized from a stable bed due to pore water exchange, cohesive sediments entrapped in the gravel during the deposition experiments were subjected to increasing shear stress conditions in the flume. No increase in suspended sediment concentration was observed likely because mobilization of sediment from a stable gravel bed driven by pore water/surface water exchange did not occur.

At the conclusion of the experiment, portions of the gravel bed were carefully removed in layers to observe the horizontal and vertical distribution of cohesive sediments within the gravel bed. Cohesive sediments were predominantly located on the leeward sides of gravel or at gravel particle contact points (Figure 4.3). The figure also shows that cohesive sediments preferentially settle within micro-topographic features in the gravel that promote conditions of low flow. Accordingly, particle shape and roughness enhance the settling of cohesive materials particularly in areas of the gravel bed where fluid shear is reduced within micro-topographic depressions on individual pieces of gravel. Once cohesive sediments settled in these quiescent zones within the gravel, they remain until the bed is disturbed.

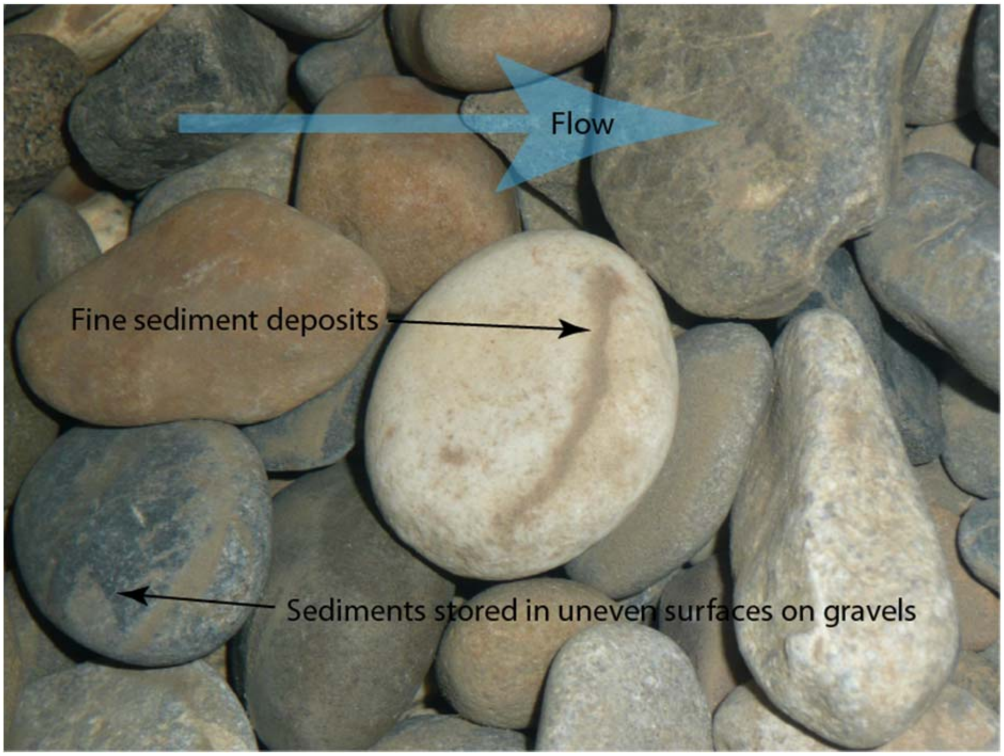


Figure 4.3 Deposition of Cohesive Sediments in Quiescent Zones within the Gravel Bed and in Micro-topographic Features on the Gravel Surface

The net mobilization of cohesive sediment from the gravel bed into the water column was very low. However, some sediment pulsing from the gravel bed into the water column was observed (refer to Figure 3.5). The pulsing pattern was relatively constant in periodicity and concentration (two concentration peaks were observed). It is hypothesized that the observed small suspended sediment pulses resulted from the erosion of fine sediments deposited on the surface of the gravel bed. The stochastic nature of the sediment remobilization into the water column is most likely related to the turbulent nature of flow at the boundary layer (Kirkbride and Ferguson, 1995). Further investigation into the nature of the pulsing, if it is an artifact of the rotating flume or it was induced by turbulence generated by the gravel bed is recommended

Previous studies demonstrate that mobility of the framework particles, which are defined as the larger bed particles which form a self-supporting and interlocking framework (Carling, 1987), of a coarse gravel bed is required to release stored fines (Diplas, 1947; Enstein, 1968; Schalchli, 1992; Rehg *et al.*, 2005; Krishnappan, 2006). The maximum rotational speed of the flume was not sufficient to create enough shear stress to mobilize the gravel bed. The PHOENICS model estimated the maximum bed shear stress generated in the flume was 1.11Pa. According to the Equation 14 (Julien, 2002),

$$\tau_c = (G - 1)\gamma_w d_i \tau_{*c} \qquad [15]$$

where, G is the specific weight of the particle, γ_w is specific weight of water, d_i is the particle diameter, the D_{50} of the bed was used and τ_{*c} is the critical shields parameter given as 0.047 for very coarse gravel, the critical shear stress required to mobilize the gravel bed used in the flume experiment was 15.9Pa which is fourteen times greater than the maximum shear stress produced in the flume.

As a surrogate to flow induced bed mobilization, the bed was agitated by hand, which resulted in the resuspension of cohesive sediments (Figure 4.4). This demonstrated that if the flume had generated flows sufficient to mobilize the gravel bed, the entrapped cohesive sediments would have very likely been released and suspended within the water column. The bed of the Elbow River was also agitated by hand showing similar results to those observed in the flume, with fine sediments easily mobilized from the disturbed bed (Figure 4.5).

Figure 4.4 Resuspension of fines from the gravel bed (due to mechanical mobilization of the gravel bed). Left Cell is Undisturbed and Right Cell has been Mechanically Agitated.

Figure 4.5 Mobilization of fine sediments through mechanical disturbance in the Elbow River bed.

Based on the results of this study, cohesive sediments stored in the Elbow River bed are most likely released when flow in the Elbow River is sufficient to mobilize framework particles of the gravel bed. Accordingly, it is necessary to quantify the critical shear stress and the corresponding critical discharge for the Elbow River bed to predict the flow conditions under which the majority of the bed stored cohesive sediments will be transported to the Glenmore Reservoir. Using Equation 15 and the sediment distributions from the gravels used in the flume experiments and the core samples taken from the Elbow River point bar, a rough estimate of the critical shear stress of the Elbow River bed was calculated. The critical shear stress for the Elbow River bed was estimated to range between 13Pa and 16Pa. More intensive bed sampling with greater spatial representation is required to refine this estimate.

4.6 Entrapment Coefficient

Sediment erosion studies conducted in flumes show that entrapment of cohesive sediment can occur but is influenced by the composition of the bed substrates (Diplas, 1947; Enstein, 1968; Schalchli, 1992; Rehg *et al.*, 2005; Krishnappan and Engel, 2006). To better describe both entrapment and cohesive sediment transport, Krishnappan and Engel (2006) developed the concept of an entrapment coefficient and used it as a parameter within a cohesive sediment transport model to more accurately describe the effects of gravel on cohesive sediment transport (erosion and deposition). The entrapment coefficient relates the mass of sediment removed from the water column and stored within the bed to bed substrate size.

In the present study, an entrapment coefficient was calculated for Elbow River gravel and compared against entrapment data for a limited number of sands and gravels (Table 4.3).

The entrapment coefficient for the Elbow River gravels was 0.2, which is 21% of the value (0.94) for gravel used by Krishnappan and Engel (2006). They found the entrapment coefficient for sand was 0.19 and 0.48 for shear stress of 0.2 and 0.4, respectively. The difference in entrapment coefficient for same sized sand was attributed to the stability of the bed which at low shear was stable but was mobilized at the higher shear stress. Krishnappan and Engel (2006) observed that a mobile sand bed used in their experiments prevented a clogging layer from forming, thus resulting in higher entrapment value than for the Elbow River gravel.

Entrapment coefficients are related to factors such as the porosity, conductivity and permeability of a given substrate (Krishnappan and Engel, 2006). Entrapment coefficients from this study and Krishnappan and Engel (2006) are plotted against substrate size, porosity and hydraulic conductivity in Figure 4.6. For consistency, only entrapment coefficients for beds which did not form clogging layers were plotted (i.e. the mobile sand bed). Figure 4.6 shows the entrapment coefficient peaks with a bed substrate D_{50} of 8mm and then decreases with increasing substrate size. The entrapment coefficient peak also coincides with inflection points on the porosity and hydraulic conductivity plots, suggesting a relationship between porosity, hydraulic conductivity and optimal entrapment. These two bed properties likely play a key role in determining the entrapment potential of various bed substrates and there is likely an optimal substrate size and bed hydrodynamic condition where fine sediment entrapment is maximized. A larger entrapment coefficient data set is required to determine optimum substrate size and distribution for entrapment.

Table 4.3 Entrapment Coefficients for Various Substrate Sizes

Bed Substrate Size D_{50} (mm)	Bed Shear Stress (Pa)	Entrapment coefficient $\propto$
21	0.48	0.2 (current study)
8	0.3	0.94 (Krishnappan 2006)
8	0.7	0.94 (Krishnappan 2006)
1	0.2	0.19 (Krishnappan 2006)
1	0.4	0.48 (Krishnappan 2006)

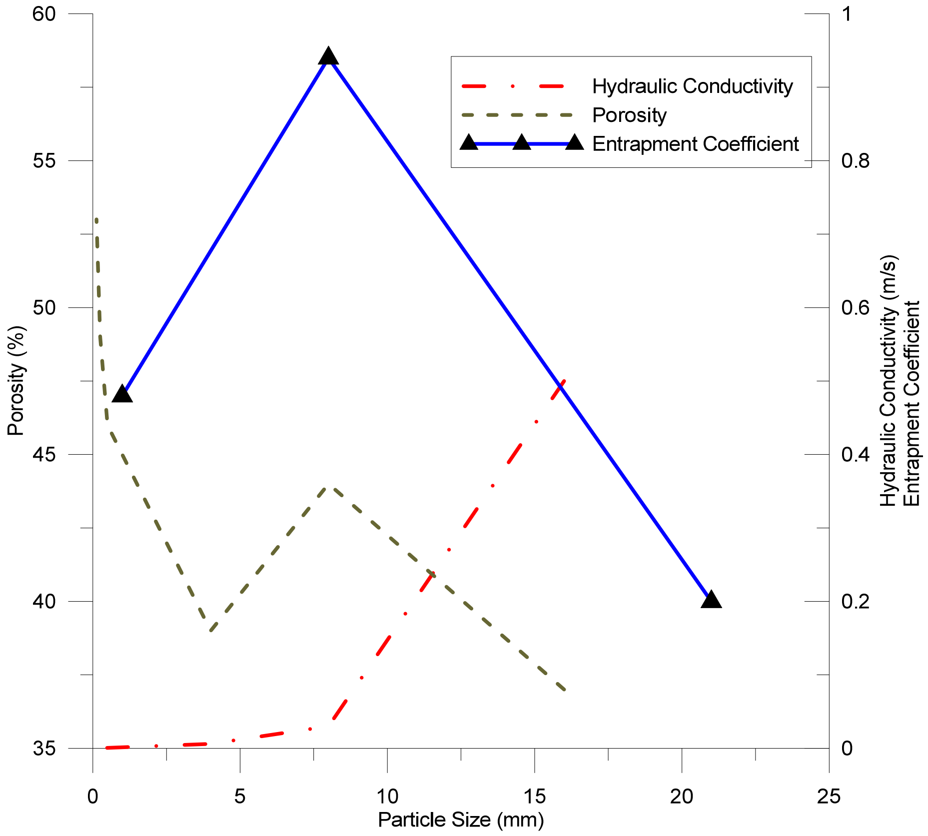


Figure 4.6 Entrapment Coefficients Plotted against Substrate Porosity and Hydraulic conductivity. Source for porosity and hydraulic conductivity values; Bear (1972).

The combined results of the present study and Krishnappan (2006) demonstrate the potential of the entrapment coefficient concept to model the flux of cohesive sediment in gravel bed rivers. The relationship between entrapment potential of a river bed based on its substrate size may be a useful tool in predicting cohesive sediment transport and storage in rivers but requires further systematic study. Further research into entrapment coefficients is required to better understand its relationship to substrate size and bed hydrodynamics.

4.7 Density and Settling Velocity

The settling velocity of cohesive sediment increases with size for small flocs to a maximum before decreasing to near zero for the much larger flocs (Krishnappan, 2007). The relationship between floc size and settling velocity of Elbow River cohesive sediment is consistent with earlier studies (Watt and Marsalek, 1994; Krishnappan, *et al.*, 1999; Krishnappan and Marsalek, 2002). Floc size plays a dual role in settling velocity based on floc density as a function of increased porosity (Droppo *et al.*, 2000). The settling velocity of cohesive sediment from the Elbow River (refer to Figure 3.9) was consistent with the results of these earlier studies, reaching a maximum of 0.37mm/s at a floc size of 50µm before decreasing to 0.07mm/s with increasing floc size (128µm) coupled to decreasing floc density. The results of the current study demonstrated that the inverse relationship between floc size and settling velocity for larger flocs was consistent with cohesive sediments collected from various sources (stormwater management ponds and natural rivers) and physical environments (Watt and Marsalek, 1994; Krishnappan, *et al.*, 1999; Krishnappan and Marsalek, 2002; Krishnappan, 2007).

4.8 Estimating Fine Sediment Storage in the Elbow River

Understanding the storage and flux of fine sediment in fluvial systems has important implications for understanding the fate of sediment-associated contaminants and nutrients in terrestrial and aquatic environments (Walling *et al.*, 1998). Several studies have been conducted to examine the storage and ecological impacts of fine sediment in gravel bed rivers (Walling *et al.*, 1998; Petticrew, 1996; Petticrew and Biickert, 1998; Brunke, 1999; Nerbonne and Vondracek, 2001; Sutherland and Gardiner, 2002; Julien and Bergeron, 2006). A series of methodological approaches have been used to estimate fine sediment storage and colmation in river beds (Lambert and Walling, 1998; Walling *et al.*, 1998; Petticrew, 1996; Petticrew and Biickert, 1998). Of the several methods previously used, sediment cores provide a reasonable approximation of fine sediment storage in gravel beds (Schalchli, 1992; Lambert and Walling, 1998; Kreutzweiser and Scott, 2001).

Core samplers were used in the present study to estimate the mass of cohesive sediment stored in a partially submerged gravel point bar of the Elbow River. The results of this analysis provide an estimate of the mass of fine sediment stored in one bed feature that is potentially available for transport into the Glenmore Reservoir during high discharge conditions. Such information is relevant to the City of Calgary in the context of drinking water supply because cohesive sediment is the primary vector for phosphorus transport which can influence the trophic status of the Glenmore Reservoir (Sosiak and Dixon, 2004). The most bioavailable particulate phosphorus forms are associated with sediment size fractions <20µm (Stone and English, 1993). The phosphate desorption potential from cohesive sediment into the water column is most pronounced in the smallest size fraction (Stone and Mudroch, 1989) which accelerate algal productivity (Stone et al., 1991).

Sosiak and Dixon (2004) reported that cohesive sediments play a critical role in the eutrophication of the Glenmore Reservoir and that it is important to quantify the mass of cohesive sediment stored within the Elbow River bed and its potential impact on water supply. Core samples acquired from the point bar found the cohesive sediment fraction stored in gravel of the Elbow River was ~ 0.5% of the total bed mass. This observation is consistent with Lambert and Walling (1998) who report that cohesive sediments accounted for less than one percent of the total sediment budget of the River Exe bed in the United Kingdom. While cohesive sediment accounts for only a small percentage of the overall bed mass, it still represents a sizable total mass of sediment available for transport. Approximately 2.4 kg/m^3 of cohesive sediment was measured in the upper 0.08m of the sampled point bar. Using aerial photography, it was estimated that the point bar from which the core samples were collected had an approximate surface area of $4{,}500m^2$, corresponding to potentially 864kg of stored cohesive sediment in its upper 0.08m. This estimate is for one point bar along the 130km of river upstream of the Glenmore Reservoir, demonstrating the overall potential mass of cohesive sediment stored in the Elbow River and available for transport into the Glenmore Reservoir. Accordingly, under flow conditions where the gravel armor layer is mobilized much of the stored fine sediment and associated nutrients would be mobilized from the bed into the water column and likely transported directly into the Glenmore Reservoir. A more systematic and detailed study of fine sediment transport and storage in the Elbow River is required to quantify and physically model this process.

4.9 Conclusions

The present study is the first to rigorously quantify: 1) the transport characteristics (critical shear stress for erosion and deposition, settling velocity and particle density) of cohesive sediment in the Elbow River; and, 2) the effect of coarse gravel on cohesive sediment entrapment. The results provide baseline data which can be used to model and further evaluate the importance of the Elbow River gravel bed as a source and sink for cohesive sediment to the Glenmore Reservoir.

Specific Conclusions of the study are:

1. Fine sediments of the Elbow River are cohesive and have properties similar to those observed in other fluvial environments;
2. The critical shear stress for deposition of cohesive sediment under plane bed conditions is 0.115Pa;
3. The critical shear stress for erosion of cohesive sediment under plane bed conditions is 0.212Pa. This value is higher than critical shear stress for reported for cohesive sediments from other Canadian rivers;
4. Settling velocity is dependent on floc density. The density of the constituent parent particles is 2.61gm/cc and approximately 2.0gm/cc for the D_{50} of 17.17µm. Particle density approached that of water (1 gm/cc) for particles greater than 100µm. The maximum settling velocity of 50µm flocs is 0.37mm/s but it decreased to 0.07mm/s for flocs with a diameter of 128µm;
5. A non-mobile gravel bed in the flume entrapped 93% of the suspended cohesive sediments in a water column. Cohesive sediments were likely transported into the

gravel bed through advective pumping driven by turbulence induced by the bed roughness;

6. During the deposition experiment with a gravel bed, cohesive sediment entrapment was more strongly influenced by the gravel bed than bed shear stress;
7. Cohesive sediments were not mobilized from a stable bed and were only released when the bed was disturbed. Cohesive sediments remained entrapped within the gravel bed due to preferential settling of fine sediment into low shear areas within the gravel matrix (quiescent zones) and deposited within micro-topographic features on the surface of gravel particles;
8. Based on in-channel measurements of a gravel point bar with sediment corers, 864kg of cohesive sediment was stored in the upper 0.08m of the point bar. Under high flow conditions exceeding the critical shear stress of the river bed, the stored cohesive sediments will be released and transported downstream into the Glenmore Reservoir; and,
9. An entrapment coefficient of 0.2 was determined for the gravel bed in the flume. A plot of entrapment coefficient with bed substrate porosity and hydraulic conductivity suggests there are optimal conditions of bed substrate size and/or composition which maximize entrapment of cohesive sediment.

4.10 Recommendations for Future Research

The results of this study improve knowledge of the cohesive sediment transport in the Elbow River but it has also highlighted areas requiring further research. These include:

1. The entrapment experiment used sorted and cleaned gravel bed. Investigations using the full substrate distribution of the Elbow River should be conducted to gain a better understanding of the entrapment and storage properties of the fully representative Elbow River bed;
2. Increased knowledge of the fate and transport of cohesive sediments into the Glenmore Reservoir and its impact on water quality is necessary from a reservoir management and water supply perspective.
3. More detailed studies are required throughout the Elbow River to rigorously quantify the mass of cohesive sediment stored in the bed;
4. Further research is necessary to quantify and model the entrapment potential of a river bed based on the bed substrate size distribution. Currently the entrapment coefficient data set is very small and insufficient for the development of model to predict the entrapment potential of a river bed based on substrate size and composition. In order to advance such a model, additional flume studies are required to determine entrapment ratios for a greater variety substrate sizes, types and mixes. Establishing a database and/or model which could predict the entrapment potential of river beds based on substrate size could become a very important and powerful tool in river management;

5. To date gravel bed entrapment studies have been conducted with only a limited number of homogenous bed substrates. Research into entrapment associated with river beds comprised of heterogeneous substrates is required to determine rates of entrapment and the influence of clogging layers. In general, all cohesive sediment entrapment studies have occurred under laboratory conditions in flumes. A progression towards studies which create conditions closer natural river beds is critical to the development of models which can accurately describe cohesive sediment transport;
6. The flume erosion experiment with a gravel bed showed a pulsing pattern to the suspended sediment concentration. The pulsing pattern was relatively constant in periodicity and concentration (two concentration peaks were observed). Further investigation into the nature of the pulsing, if it is an artifact of the rotating flume or it was induced by turbulence generated by the gravel bed is recommended; and

7. The concept of bed contraction and dilation (Marquis and Roy, 2012) suggest there is the potential for cohesive sediment mobilization from a bed in which the framework particles are not mobilized. Further study is required into the release of cohesive sediments from the bed when flows approach the critical shear stress of the bed.

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