The Effect of Discharge Conditions on Morphological Development and Bed Load Transport Rates in an Unconfined Alluvial Meandering Stream

by

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ABSTRACT

THE EFFECT OF DISCHARGE CONDITIONS ON MORPHOLOGICAL DEVELOPMENT AND BED LOAD TRANSPORT RATES IN AN UNCONFINED ALUVIAL MEANDERING STREAM

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Understanding fluvial processes in rivers and streams and their interactions with each other enable for more effective channel designs, improved erosion control measures, and more resilient systems. The use of an unconfined river basin flume (5.6 m in length x 1.9 m in width) allowed for analysis of the interactions between sediment transport rates, bed development, and planform morphological adjustments in an unconfined alluvial meandering stream. Three tests were completed including one quasi-unsteady hydrograph experiment. It was found that the largest bank morphological adjustments coincided with considerable bed development and sediment transport rates; agreeing with previous field and laboratory observations. Morphological evolution appears to follow an exponential growth profile, with the majority of bed development and bank erosion occurring during the early stages of a run or during the rising limb of the hydrograph. Results from this research proposed relationships between discharge, sediment transport and channel morphology in alluvial meandering streams.
Co-Authorship Statement

The work within this thesis was completed by the present author with the collaboration of Dr. Andrew D. Binns. Dr. Binns provided valuable feedback throughout the research process including the assistance of setting up the experimental procedures, data analysis, and review of the text. The contents of this thesis will be submitted for two publications; one focusing on the morphological response of the meandering channel and the second focused on the sediment transport rates and effect of unsteadiness. These papers will be submitted for publication as follows:

Sullivan, C., & Binns, A. D. Morphological development of an alluvial meandering stream to varying flow conditions in a laboratory flume. To be submitted.

And

Sullivan, C., & Binns, A. D. Sediment transport rates in an unconfined alluvial meandering stream. To be submitted.
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List of Symbols

\( a \)  Coefficient in Yalin equation

\( B \)  Channel width (m)

\( B_s \)  Roughness function

\( D_i \)  Intermediate diameter of an ellipsoidal particle (m)

\( D_L \)  Largest diameter of an ellipsoidal particle (m)

\( D_s \)  Shortest diameter of an ellipsoidal particle (m)

\( D_{50} \)  Median grain size of sediment (m)

\( F_i \)  Fractional proportion of a sediment class in the bed sample (by mass)

\( Fr \)  Froude Number

\( g \)  Gravitational constant (m/s²)

\( g_s \)  Sediment transport weight per unit stream width (kg/ms)

\( h \)  Flow depth (m)

\( h_p \)  Flow depth at the upstream end of the channel at the peak of the hydrograph (m)

\( h_0 \)  Flow depth at the upstream end of the channel at the initial condition (base flow) (m)

\( J_0(\theta_0) \)  Bessel function

\( K_s \)  Granular roughness height (m)

\( L \)  Length of the stream path (m)

\( l_c \)  Longitudinal coordinate along channel centerline (m)

\( n \)  Transverse coordinate along channel centerline (m)

\( P \)  The unsteady flow parameter

\( p \)  Porosity of the sediment (m³/m³)

\( p_i \)  Fractional proportion of a sediment class in the transport sample (by mass)
Q \quad \text{Flow rate (m}^3/\text{s}) \\
Q_t \quad \text{Volumetric transport rate (m}^3/\text{s}) \\
q_b \quad \text{Volumetric bed load transport rate per unit stream width (m}^3/\text{s}) \\
q_t \quad \text{Volumetric transport rate per unit stream width (m}^2/\text{s}) \\
R \quad \text{Hydraulic radius (m)} \\
Re \quad \text{Reynolds Number} \\
Re_* \quad \text{Roughness Reynolds Number} \\
S \quad \text{Longitudinal bed slope (m/m)} \\
S_0 \quad \text{Initial longitudinal slope of the bed (m/m)} \\
SF \quad \text{Shape factor} \\
s \quad \text{Coefficient in Yalin equation} \\
t \quad \text{Time (s)} \\
t_d \quad \text{Duration of the hydrograph (s)} \\
t_r \quad \text{Duration of the rising limb of the hydrograph (s)} \\
u_* \quad \text{Shear velocity (m/s)} \\
u_{*0} \quad \text{Shear velocity at the upstream end of the channel at the initial condition (base flow) (m/s)} \\
V \quad \text{Mean flow velocity (m/s)} \\
V_p \quad \text{Velocity of flow at the upstream end of the channel at the peak of the hydrograph (m/s)} \\
V_0 \quad \text{Velocity of flow at the upstream end of the channel at the initial condition (base flow) (m/s)} \\
W \quad \text{Specific gravity of the sediment} \\
W_t \quad \text{Total bed load (kg)} \\
W_t^* \quad \text{Dimensionless total bed load} \\
z_b \quad \text{Bed height (m)} \\
\beta \quad \text{Function of sediment diameter}
\( \gamma_s \quad \text{Specific weight of sediment (kg/m}^2\text{s}^3) \)

\( \gamma_w \quad \text{Specific weight of water (kg/m}^2\text{s}^3) \)

\( \Delta x \quad \text{Change in distance along the stream path (m)} \)

\( \eta \quad \text{Dimensionless number for transverse coordinate} \)

\( \eta_s \quad \text{Relative tractive force} \)

\( \theta \quad \text{Deflection angle at any channel centerline location (radians)} \)

\( \theta_0 \quad \text{Initial deflection angle (radians)} \)

\( \Lambda_M \quad \text{Meander wavelength (m)} \)

\( \nu \quad \text{Kinematic viscosity (m}^2\text{/s)} \)

\( \Xi \quad \text{Material number} \)

\( \xi_c \quad \text{Dimensionless number for longitudinal coordinate} \)

\( \rho \quad \text{Density of water (kg/m}^3) \)

\( \rho_s \quad \text{Density of the sediment (kg/m}^3) \)

\( \sigma \quad \text{Sinuosity} \)

\( \tau_0 \quad \text{Bed shear stress (Pa)} \)

\( \tau^* \quad \text{Mobility number} \)

\( \tau_{cr}^* \quad \text{Critical mobility number} \)

\( \Phi \quad \text{Einstein’s Phi} \)

\( \psi_i \quad \text{Fractional bed load number} \)
Chapter 1: Introduction

1.1 Overview

Rivers have been vital for the growth of human civilization as people developed communities on their banks, navigated the waters, and used the water for consumption and recreation purposes. But much like the advancements and growths in human society since the first communities, the rivers too have also been developing. Adjustments to the channel shape, slope, and cross-sectional geometries are ever evolving to the changing inputs of sediment and flow rates. Some of these adjustments take years or decades before they are noticeable, but others happen suddenly and can be quite substantial. The impacts of high flows on large channel adjustments were witnessed in Southern Alberta in 2013, when the Bow River, Elbow River, and Highwood River moved up to 150 meters in some places (Shahzad, 2015), causing severe damage to many communities including Calgary. The channel migration and subsequent flooding in Calgary caused a reported damage cost near $5 billion (Calgary Expert Management Panel on River Flood Mitigation, 2014).

River mechanics encompasses the analysis of open channel hydraulics and sediment transport. It can be clearly seen from the example of Calgary in 2013 why this field requires further investigation and why other researchers have highlighted the impacts to human society that river degradation poses (Arthington, 2013; Dudgeon et al., 2006). River mechanics is important for engineers and scientists to investigate as the research can improve tools to better predict how rivers will migrate and evolve, especially in response to high flow events. This is especially important as many people live and work along riverbanks. Pearce (2006) highlights that 10 percent of all Europeans either live or work beside a river or stream. The ability to better predict channel morphology and protect communities from expensive damages will become paramount as the evolving climate, population growth, and land use changes can lead to increased flow magnitude and frequency (Pahl-Wostl et al., 2013; Thompson & Croke, 2013).

It is known that rivers strive to reach equilibrium and this is often achieved by reducing the channel slope through creation of a meandering pattern (da Silva, 2006, 2015). The erosion and growth of meanders can impact the land and property at the river banks, as such; stabilization practices are implemented by engineers to protect the banks from lateral migration (Kawai & Julien, 1996). In addition to bank movement, the riverbed is also changing in elevation as sediment is deposited or scoured during the channel forming process, which can affect instream structures such as a bridge pier. The use of
rudimentary sediment transport equations within common modelling software, such as HEC-RAS, is the current practice for engineers, but further refinement of those equations, especially in a laterally unconfined system, is required to better predict and model complex morphological processes in rivers. The importance of connecting sediment supply with the morphology processes was highlighted by Sear, who stated that “each component of the channel morphology is connected by the continuity of the sediment system of supply-transport-storage” (Sear, 1994, p. 171).

Among the previous laboratory studies that have been the basis for the current understanding of sediment transport and river mechanics development are Einstein (1942, 1950), Meyer-Peter & Muller (1948), and Guy et al. (1966). Others have utilized laboratory flumes in the development and validation of sediment transport equations, such as Yalin (1963) and Engelund & Hansen (1967). These studies provided the foundation for the future growth and understanding in the river mechanics field. Although most of these studies looked to identify a relationship between flow and bed load transport, some authors (Einstein, 1950; Guy et al., 1966) looked into the impact of the morphological developments in the channel. Recently, the desire to better understand the whole dynamic processes in a channel has come to the forefront (Nanson & Knighton, 1996). Field investigations have been undertaken to examine this dynamic morphological response in nature (Eaton & Lapointe, 2001; Engel & Rhoads, 2012), while previous laboratory flume studies have also examined these processes (Lajeunesse et al., 2010; Song et al., 2016; Van de Lageweg et al., 2014; Van de Lageweg et al., 2013; van Dijk et al., 2013; van Dijk et al., 2012). Although much research has recently been completed in this field, the need for further physical experimental analysis is required, especially for meandering channels.

The research completed in this thesis investigates the relationship between discharge, sediment transport and the morphological changes in the stream. The research will be examined in a laboratory unconfined meandering channel, which is more reminiscent of a natural system. The outcomes will expand on the current state of the science and provide feedback on existing theorems and ideas. This will help ensure that the current practices being implemented by engineers around the world are appropriate and comprehensive.
1.2 Goals

The goal of this research is to investigate the morphological adjustments in alluvial meandering streams in response to varying discharge events. To provide a complete analysis of the dynamic response of the channel to varying flow conditions, the research will focus on the following objectives:

1. Investigate the response of sediment transport rates in alluvial meandering streams to varying flow conditions; and
2. Quantify the development time of the stream and the temporal adjustments in the bed and planform morphology

These objectives will be completed in a river basin flume in the University of Guelph’s Water Resources Laboratory with a meandering stream having a medium value of stream sinuosity and two full meander wavelengths. The laboratory meandering stream will be unconfined, allowing for morphological adjustments of both the bed and banks. Three experimental runs will be completed in the present research; two runs will use steady flow conditions and one run will investigate the effects of unsteady flow by using a quasi-unsteady hydrograph. Further information regarding the experimental set-up will be provided in the body of the thesis. Supplemental hydraulic modelling will be completed to investigate the accuracy of the sediment transport and morphological modules against the measured results.

Previous experimental studies in this field have mostly been completed in flumes with confined banks. The validity of these studies is under the pretense that the bed form development process occurs in a much faster time scale than the bank migration processes (Eaton & Church, 2009). However, further investigation into the inter-relationship of bank morphology with sediment transport rates and bed morphology is required to provide a better understanding of these effects when large bank migrations do occur, such as those witnessed in Calgary in 2013. While most of these large flow events that cause large migration and erosion damage often involve the flow depth exceeding the height of the banks, the variation of discharge in the present research was confined within the main channel banks. Limiting the conditions to flow depths within the channel also provides a systematic and controlled approach to the research process.
1.3 Thesis Structure

This thesis is organized in the monograph format as outlined in the University of Guelph’s 2017-18 Graduate Calendar.

The thesis is comprised of chapters examining the fundamentals of fluid mechanics in open channels, a literature review of completed studies, the methodology for the present research, and results from the present research. The results section is organized in five subsections looking at the sediment transport rates, bed morphological development, planform morphology, the effect of unsteady flow, and a comprehensive analysis.
Chapter 2: Fundamentals Processes

This chapter is organized in four sections including: flow mechanics, sediment transport, planform definition, and the effect of the shape factor. The first two sections examine existing hydraulic and sediment transport concepts, the third section examines existing geomorphic processes in streams, and the final section examines sediment characteristics and their impact on the hydraulics and morphological processes in streams.

2.1 Flow Mechanics

Fundamental studies on flowing water provide the basis for further concepts discussed and studied in this research. The two main fundamental theorems regarding fluids mechanics are the Reynold’s Number and the Froude Number; both numbers quantify the flow conditions of the fluid. The Reynold’s Number describes the flow regime of the fluid by distinguishing a range for laminar, turbulent, and transitional flow. For open channels, turbulent flow is achieved once the Reynold’s Number exceeds 600. The Reynold’s Number, \( Re \), can be described by the following equation:

\[
Re = \frac{VR}{\nu}
\]

\textit{Equation 1}

Where \( V \) is mean flow velocity, \( R \) is the hydraulic radius (described as the cross sectional area divided by the wetted perimeter), and \( \nu \) is the kinematic fluid viscosity (calculated from water temperature). The kinematic fluid viscosity can be impacted by suspended solids within the flow (Brunner, 2010, 2016b; Simons & Richardson, 1966; Simons et al., 1963). The validity of using the mean flow velocity in an alluvial channel was highlighted by Einstein (1950) for flows in the main channel.

The other dimensionless number that describes the flow classification is the Froude Number. The Froude Number, \( Fr \), distinguishes the state of the flow in an open channel as \( Fr < 1 \) being sub-critical flow, \( Fr > 1 \) being super-critical flow, and \( Fr = 1 \) being critical flow. The Froude number can be described by the following equation:
\[ Fr = \frac{V}{\sqrt{gR}} \]

*Equation 2*

Where \( g \) is the gravitational constant. Having both the Froude Number and Reynolds Number in the same state and regime as those found in natural open channel streams ensures that the experimental research completed is applicable in real life practice/modelling.

The Roughness Reynolds Number, \( Re_\ast \), describes the flow at the boundary with the bed sediment (Masad, 1995). Based on the size of the sediment, the roughness Reynolds Number can be calculated from the following equation:

\[ Re_\ast = \frac{u_\ast K_s}{v} \]

*Equation 3*

Where \( u_\ast \) is the shear velocity and \( K_s \) is the granular roughness height. The granular roughness height can be simplified to two times \( D_{50} \), where \( D_{50} \) is the median grain size of sediment. The shear velocity can be calculated as:

\[ u_\ast = \sqrt{gSh} \]

*Equation 4*

Where \( S \) is the longitudinal bed slope and \( h \) is the flow depth. The longitudinal bed slope can be utilized within this equation if the flow is uniform (slope of the energy grade line is equal to the bed slope).

As described by Sturm (2001), Yalin and Karahan (1979) compiled additional data to the original data of Shields (1936) to analyze the transition zones of the flow regimes with respect to the roughness Reynolds Number. For \( Re_\ast < 1 \) the flow is laminar/smooth turbulent, \( 1 < Re_\ast < 70 \) the flow is in the transitional phase, and \( Re_\ast > 70 \) the flow is fully rough turbulent. Obtaining laboratory results with a \( Re_\ast \) greater than seventy is quite difficult in many experiments. As such, roughness Reynolds Number within the transitional phase are adequate for flume experiments. Previous flume studies have shown that roughness Reynolds Numbers in the transitional phase can produce morphologically similar results to those found from field data (De Sutter et al., 2001; Guy et al., 1966; Jackson II, 1975; Madej et al., 2009).

Sediment transport is based on a relationship between the shear force of the flow and the resistive force of the channel bed sediment. The inception of motion occurs once the fluid shear stress exceeds the resistive
forces of the sediment on the bed. The relative tractive force term introduced in Yalin & da Silva (2001) describes this relationship.

\[ \eta_* = \frac{\tau^*}{\tau_{cr}^*} \]

*Equation 5*

Where \( \eta_* \) is the relative tractive force, \( \tau^* \) is a function of the fluid shear stress, and \( \tau_{cr}^* \) is the critical shear stress for motion inception found through Shield’s diagram. The relative tractive force can also describe the type of sediment transport occurring within the stream. Bed load occurs exclusively if the ratio between the forces remains below 10 (1 < \( \eta_* \) < 10); however, once \( \eta_* \) exceeds 10, suspended load in addition to bed load occurs. In addition to bed load and suspended load, wash load is the supply of sediment to the stream from the supplying watershed; however, wash load is generally fine sediment particles that have minimal impact on the morphological development of the stream beds (Naqshband & McElroy, 2016). The value for \( \tau^* \) can be found through the following equation.

\[ \tau^* = \frac{\tau_0}{(\gamma_s - \gamma_w)D_{50}} \]

*Equation 6*

Where \( \tau_0 \) is the bed shear stress, \( \gamma_s \) is the specific weight of the sand, and \( \gamma_w \) is the specific weight of the fluid (water). Bed shear stress can be calculated as follows.

\[ \tau_0 = \gamma_w Sh \]

*Equation 7*

The critical shear stress value is related to the empirical Shield’s diagram. The development of a function for the Shield’s diagram has been undertaken by previous researchers (Cao et al., 2006; Yalin & da Silva, 2001). According to Yalin and da Silva (2001), the critical shear stress value was calculated as a function of the dimensionless material number, \( \Xi \).

\[ \Xi = \sqrt[3]{\frac{\gamma_s D_{50}^3}{\rho v^2}} \]

*Equation 8*

\[ \tau_{cr}^* = 0.13\Xi^{-0.392}e^{-0.01 \Xi^2} + 0.045[1 - e^{-0.068\Xi}] \]

*Equation 9*
2.2 Sediment Transport

Many transport equations exist for sediment movement in open channels. Some of these equations have been based on physical studies, while others have been developed solely on physical principles. Each of these methods will be briefly described. At the present time, there is no universal acceptance as to which method produces the most accurate results for natural systems (Garcia, 2008a). Garcia (2008b) produced the most comprehensive review of the many existing bed load transport equations developed in the past 60 years; upwards of fifteen different equations are highlighted. However, for the purpose of this research, only a few common equations will be evaluated against the experimental results; namely, Bagnold’s (1966), Meyer-Peter & Muller (1948), Yalin (1963), and Engelund & Hansen (1967).

Most of the above bed load equations determine “Einstein’s Phi”, \( \varphi \), (Einstein, 1950) which in turn is used to calculate the volumetric bed load transport rate per unit stream width, \( q_b \). Since the experiments assume that bed load is the only form of sediment transportation, the total volumetric transport rate per unit stream width, \( q_t \), is equal to \( q_b \).

\[
\varphi = \frac{\rho^{1/2} q_t}{y_s^{1/2} D_{50}^{3/2}}
\]

*Equation 10*

To find the total volumetric transport rate of sediment, \( Q_t \), the total volumetric transport rate per unit stream width is multiplied by the channel width.

2.2.1 Bagnold equation

The first method of bed load transport that will be investigated is the Bagnold equation (Bagnold, 1966). Bagnold used physics’ equations and energy principles to develop his transport theorem; it excludes any empirical data during the development of the equation. The Bagnold equation is shown below.

\[
\varphi = B_s \beta \tau^*^{1/2}(\tau^* - \tau^*_{cr})
\]

*Equation 11*

Where \( B_s \) is a roughness function and \( \beta \) is a function of the sediment diameter. The value for \( B_s \) can be found through the following equation based on the roughness Reynold’s Number.
2.2.2 Meyer-Peter and Muller equation

The Meyer-Peter and Muller equation was developed through empirical research completed on a flume with varying sediment sizes (Meyer-Peter & Müller, 1948). The Meyer-Peter and Muller equation is one of the earliest transport equations developed and continues to be one of the most commonly used transport equations to date. The equation has been further investigated in the past fifteen years to try to improve its accuracy (Wong, 2003; Wong & Parker, 2006); however, for the current research, the original equation will be utilized.

\[
B_s = (2.5 \ln Re_* + 5.5)e^{-0.07 \ln Re_*}2.55 + 8.5(1 - e^{-0.0594(\ln Re_*)2.55})
\]

*Equation 12*

\[
\varphi = 8.0(\tau^* - \tau_{cr}^*)^{3/2}, \text{ with } \tau_{cr}^* = 0.047
\]

*Equation 13*

The Meyer-Peter and Muller equation is also one of seven transport equations that can be used in HEC-RAS modelling software (Brunner, 2010, 2016b). However, the Meyer-Peter and Muller equation is only used in solving for the bed load transport.

2.2.3 Yalin equation

The Yalin equation was developed through a semi-empirical approach (Yalin, 1963). The Yalin equation is shown below.

\[
\varphi = 0.635s\sqrt{\tau^*} \left[ 1 - \frac{1}{as} \ln(1 + as) \right]
\]

*Equation 14*

Where \(s\) and \(a\) are constants found through the following equations.

\[
s = \frac{\tau^* - \tau_{cr}^*}{\tau_{cr}^*}
\]

*Equation 15*
\[ a = 2.45 \frac{\tau^*}{W^{0.4}} \]

Equation 16

Where \( W \) is the density of the sediment divided by the density of the fluid (water).

2.2.4 Engelund and Hansen equation

The Engelund and Hansen equation (Engelund & Hansen, 1967) was developed from laboratory data (Guy et al., 1966). The Engelund and Hansen equation is an extension of Bagnold’s equation, utilizing stream power (Gyr & Hoyer, 2006). The Engelund and Hansen transport equation was synthesized by Hossain and Rahman (1998) as shown below with a direct correlation to bed load transport rate.

\[ g_s = 0.05y_s V^2 \sqrt{\frac{D_{50}}{g \left( \frac{y_s}{y_w} - 1 \right)}} \left[ \frac{\tau_0}{(y_s - y_w)D_{50}} \right]^{3/2} \]

Equation 17

Where \( g_s \) is the sediment transport weight per unit stream width (kg/ms). The Engelund and Hansen method is also one of the options in the HEC-RAS model (Brunner, 2010, 2016b). Unlike the Meyer-Peter and Muller equation, the Engelund and Hansen equation is a total load equation accounting for both bed load and suspended load. The Engelund and Hansen equation can also be employed to investigate the transport of multiple sediment classes (Downer et al., 2015); this is completed with the implementation of a proportion coefficient and the adjustment of the \( D_{50} \) to the \( D_{l-th} \) sediment class.

2.3 Meandering Stream Planform Geometry

Different sinuosity can describe stream courses; often steeper streams are straighter while lower sloped channels have a higher sinuosity value. This is attributed to the streams trying to self-adjust to reach equilibrium. The sinuosity of the stream can be defined as:
Where $\sigma$ represents sinuosity, $L$ is the length of the stream path, and $\Lambda_M$ is the meander wavelength.

According to Leopold & Langbein (1966) and Langbein & Leopold (1966), meandering streams can be approximated with the following sine-generated stream.

$$\theta = \theta_0 \cos\left(2\pi \frac{l_c}{L}\right)$$

Equation 19

Sinuosity can also be defined from the initial deflection angle of the stream.

$$\sigma = \frac{1}{J_0(\theta_0)}$$

Equation 20

This stream definition has been implemented in previous laboratory research (Binns & da Silva, 2009; da Silva et al., 2006; Ebrahimi, 2015; He & Chen, 2013; Termini, 2009, 2015; Xu & Bai, 2013). Where $\theta$ is the deflection angle at any $l_c$, $\theta_0$ is the initial deflection angle measured in radians ($l_c = 0$), and $l_c$ is the longitudinal coordinate along the channel centerline (see Figure 1). $J_0(\theta_0)$ is the Bessel function of the first kind and zeroth order.

$$J_0(\theta_0) \approx 1 - 2.2499997 \left(\frac{\theta_0}{3}\right)^2 + 1.2656208 \left(\frac{\theta_0}{3}\right)^4 - 0.3163866 \left(\frac{\theta_0}{3}\right)^6 + 0.0444479 \left(\frac{\theta_0}{3}\right)^8$$

$$- 0.0039444 \left(\frac{\theta_0}{3}\right)^{10} + 0.0002100 \left(\frac{\theta_0}{3}\right)^{12}$$

Equation 21
The wavelength of the meander has been found to depend on the width of the channel (Langbein & Leopold, 1966; Yalin, 1992). Yalin (1992) describes this relationship between channel width and meander wave below.

\[ A_M = 2\pi B \]

*Equation 22*

This definition has been utilized in previous laboratory research (Binns & da Silva, 2009, 2015; Ebrahimi, 2015; Termini, 2009, 2015; Termini & Piraino, 2011).
The position of a point in the channel can be described by the channel coordinates \( l_c \) and \( n \) (Figure 1) or the dimensionless numbers associated with the coordinates.

\[
\xi_c = \frac{l_c}{L}
\]

Equation 23

\[
\eta = \frac{n}{B}
\]

Equation 24

The adjustment of the mean bed elevation through the channel is governed by the transport continuity equation.

\[
(1 - p) \frac{\Delta z_b}{\Delta t} = - \frac{\Delta q_b}{\Delta x}
\]

Equation 25

Where \( p \) is the porosity of the sediment, \( \Delta z_b \) is the change in bed height, \( \Delta t \) is the change in time, and \( \Delta x \) is the change in the distance along the stream path. Further developments to bed form and planform equations have been undertaken by previous researchers (Seminara, 2006).

2.4 Sediment Shape Factor

Many of the equations listed above rely on the mean grain size diameter of the sediment and assume that all the sediment particles are rounded spheres. The adjustment for particle shape irregularities must be taken into consideration when using these equations. The impact of the shape factor on settling rates was investigated by Komar & Reimers (1978) and found that utilizing a shape factor better predicted grain settling velocities than using nominal grain size diameters. The nominal grain size diameter refers to the diameter determined using a sieve test and the application of the shape factor adjusts the nominal value to that of a sphere with the same weight, thus making it useable in bed load transport equations. Although only testing two different shape parameters, Komar & Reimers (1978) found that the shape factor performed better than the sphere measurement. The shape factor was developed by two separate researchers Corey (1949) and Malaika (1949), published in Albertson (1953) and McNown & Malaika (1950), respectively. This shape factor has since become standard within the research field, and expressed as (Sturm, 2001):
Equation 26

\[ SF = \frac{D_s}{\sqrt{D_i D_l}} \]

Where \( SF \) is the shape factor, \( D_s \) is shortest diameter of an ellipsoidal particle, \( D_i \) is the intermediate diameter, and \( D_l \) is the largest diameter. For a perfect sphere, the \( SF \) is a value of 1; however, for ellipsoidal particles the \( SF \) value is less than 1. For natural sands the shape factor has been found have an average value of 0.7 (U.S. Inter-Agency Committee on Water Resources, 1957). The relationship between the nominal diameter and spherical fall diameter to be used in the sediment transport equations is seen below in Figure 2.

Figure 2: Relationship between nominal diameter and fall diameter for varying shape factors (U.S. Inter-Agency Committee on Water Resources, 1957, p. 32)
Chapter 3: Literature Review

3.1 Previous Laboratory Research

Previous laboratory research has provided insights into channel morphology and sediment transport rates for fluvial systems. The development of the bed load transport equations are the basis for understanding how the sediment particles move. However, to ensure that the equations are accurate and valid, researchers have undertaken many laboratory flume experiments to better understand the phenomenon of sediment transport and make improvements to the existing equations. In fact, some of the equations discussed in Section 2.2 were developed from some of the first flume experiments investigating sediment transport. Although many experiments have been completed since Meyer-Peter and Muller’s findings in 1948, the focus of this section will be on pertinent research and major findings from within the past decades. The importance of flume studies is highlighted by Yager et al. (2015), as the laboratory experiments have been fundamental in bed load transport equation development, bed form dynamics analysis, and meandering channel stability.

The discussion of these studies will be organized in four categories focused on two factors, steady flow versus unsteady flow, and confined banks versus unconfined banks. Additional emphasis will be put on studies in which the flows occur in a meandering channel as opposed to straight channels. Straight channel flumes are often found in laboratory settings, but natural streams and rivers are rarely straight. Therefore, it is important for researchers to investigate the impacts meanders have on sediment transport because that is how streams and rivers evolve in the natural environment. Studies containing unconfined banks are important in better understanding the morphological changes that occur within a stream. This is important for both planform adjustments but also bed form adjustments as confined bank studies may over-predict or incorrectly predict the erosion and deposition zones in the channel. Once again, it is important for research to investigate experiments that closely resemble natural systems. The growth of this field to gain a further understanding of sediment transport and morphological changes of natural riverine systems is required.
3.1.1 Steady Flow and Confined Banks

Undoubtedly, the area with the greatest amount of literature is that of flume studies completed in a confined bank flume with steady flow conditions. The channels are often rectangular, while the banks are often acrylic or acrylic glass. A layer of bed sand/gravel is added on top of the flume bed for analysis of bed load transport rates and bed form development. Researchers have completed their studies using straight flumes and meandering channels. Table 1 highlights the experimental research undertaken in this field.

De Sutter et al. (2001) highlight the sediment transport research completed in laboratories during the 1980s and 1990s, but the amount of studies is minimal and the focus of these studies is exclusively on bed load transport. Since the turn of the century, the number of laboratory studies have been increasing. A review of recent laboratory studies has been published by Gunsolus and Binns (2018).
<table>
<thead>
<tr>
<th>Author</th>
<th>Discharge (m³/s)</th>
<th>Width (m)</th>
<th>Meandering</th>
<th>Slope (m/m)</th>
<th>Sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baptist (2003)</td>
<td>0.081-0.155</td>
<td>0.80</td>
<td>N/A</td>
<td>Horizontal</td>
<td>Sand</td>
</tr>
<tr>
<td>Venditti et al. (2005)</td>
<td>0.0546-0.0759</td>
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<td>N/A</td>
<td>0.00055-0.0012</td>
<td>Sand</td>
</tr>
<tr>
<td>Madej et al. (2009)</td>
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<td>0.75</td>
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<td>0.0012</td>
<td>Sand</td>
</tr>
<tr>
<td>Nelson (2010)</td>
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<td>2.75</td>
<td>N/A</td>
<td>0.013</td>
<td>Gravel</td>
</tr>
<tr>
<td>Lajeunesse et al. (2010)</td>
<td>0.000033-0.0005</td>
<td>0.096</td>
<td>N/A</td>
<td>0.002-0.06</td>
<td>Sand-Gravel</td>
</tr>
<tr>
<td>Chen et al. (2017)</td>
<td>0.002-0.008</td>
<td>0.3</td>
<td>N/A</td>
<td>0.035-0.105</td>
<td>Sand</td>
</tr>
<tr>
<td>Nelson et al. (2015)</td>
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<td>0.154-0.216</td>
<td>Bank width varies</td>
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<td>Sand</td>
</tr>
<tr>
<td>da Silva et al. (2006)</td>
<td>0.0184-0.0253</td>
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<td>Yes</td>
<td>1/1000-1/1120</td>
<td>Sand</td>
</tr>
<tr>
<td>Binns &amp; da Silva (2009)</td>
<td>0.007-0.0138</td>
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<td>Yes</td>
<td>1/400-1/125</td>
<td>Sand</td>
</tr>
<tr>
<td>Termini &amp; Piraino (2011)</td>
<td>0.007-0.019</td>
<td>0.5</td>
<td>Yes</td>
<td>0.00371</td>
<td>Sand</td>
</tr>
<tr>
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<td>0.0055</td>
<td>Rigid Bed</td>
</tr>
<tr>
<td>Binns &amp; da Silva (2015)</td>
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<td>0.3-0.8</td>
<td>Yes</td>
<td>1/250-1/130</td>
<td>Sand</td>
</tr>
<tr>
<td>Termini (2015)</td>
<td>0.0012</td>
<td>0.5</td>
<td>Yes</td>
<td>0.00371</td>
<td>Sand</td>
</tr>
</tbody>
</table>

Baptist (2003) completed six tests on a 35 m long, 80 cm wide flume with a 9 cm thick sand layer ($D_{50}$ of 0.321 mm) to investigate the impacts of vegetation on decreasing bed shear stress. Although this study doesn’t focus on the bed load transport or morphological changes, it is valuable as those two factors are...
dependent on the bed shear stress. Baptist (2003) used a combination of measured Reynolds stress profiles and a 1D numerical model (Delft3D) to investigate reduction in bed shear stress; for a discharge of 0.101 m³/s the vegetation produced a near 80% reduction in bed shear stress (1.07 N/m² to 0.22 N/m²). However, the measured sediment transport rates are in excess of the estimated rates from the model; the author attributes this to increased turbulence levels at the vegetation causing additional suspended transport (Baptist, 2003). Baptist (2003) also investigated the bed profile. A vertical erosion pattern was observed and few bed forms were present. However, the impact of vegetation on morphological responses cannot extend to the same environment with an unvegetated condition (Lazarus & Constantine, 2013). This also applies to sediment transport.

Conversely, Venditti et al. (2005) examined the development of bed forms in a 15.2 m long, 1 m wide flume with quartz sand ($D_{50}$ of 0.5 mm) while recirculating both water and sediment. No sediment transport rates were reported by the authors. Five experimental runs were completed with different steady flow rates. The results of the fifth experimental run ($Q = 0.0546$ m³/s and Reynolds stress of 0.35 N/m²) were published showing a triangular-like growth of the bed forms until they reached the walls. The initial bed form defect regularly grew in both height and length (Venditti et al., 2005); this equal vertical and horizontal erosion/deposition pattern is in contrast to what Baptist (2003) observed.

Madej et al. (2009) utilized a 12 m long, 75 cm wide flume to simulate aggradation and degradation cycles of a real world river reach. A sediment feeding system was utilized for the aggradation phases; the composition of the sediment fed to the channel was the same as that of the bed ($D_{50}$ of 1.0 mm). Digital elevation models (DEMs) were developed after each phase of the study to visualize the erosion and deposition zones, which were both vertical and horizontal in nature. The results of the laboratory study matched up with the observation from the real world reach, including armouring and bed coarsening during degradation phases (Madej et al., 2009).

Nelson (2010) analyzed the development of bars in a gravel bed 80 m long, 2.75 m wide flume ($D_{50}$ of 11 mm) at the University of California, Berkeley. The results of the study were also depicted in a DEM showing both vertical and lateral sorting of the sediment, with local lateral transport becoming more size-selective at the downstream end of the bar (Nelson, 2010).

Lajeunesse et al. (2010) utilized a 2.4 m long, 9.6 cm wide flume to investigate the motion of sediment particles under varying flow and slope conditions. Three experimental series were completed with different shaped particles in the flume (triangle, square, and circle). Utilizing a high speed camera, the researchers were able to witness the bed load transport of individual particles in the bed. The results showed that particles exhibit intermittent motion, in that the particles would move in short bursts and then
begin a period of rest before another burst of movement downstream. The movements of these particles were high at the initial flow before exponentially decreasing as the sediment exited the flume, reaching steady state after about 2 minutes.

Chen et al. (2017) analyzed bed form development and its effect on stabilization in an 8 m long, 0.3 m wide flume with a 10 cm thick gravel layer ($D_{50}$ of 8.89 mm). The research consisted of twenty experiments with varying channel slopes and steady flow rates. The results of this research suggest that channel stabilization can occur with the development of bed form features, such as steps, cascades, and rapids (Chen et al., 2017). The slopes used in these experiments were steep (greater than 3.5%), but other research completed on steep streams has shown that the majority of flow resistance occurs at steps (Curran & Wohl, 2003).

Utilizing a varying bank to bank width, by implementing a sinusoidal function to the banks, Nelson et al. (2015) examined the impact of changing sediment supply on a 9.14 m long, 21.6 cm wide flume. The varying bank to bank width caused the development of pools to occur at the narrow sections, while riffles occurred at the wider sections (Nelson et al., 2015). This was also visually evident in the DEMs produced through the study. The channel slope adjusting to the sediment inputs mainly offset the impact of changing sediment supply to the flume (Nelson et al., 2015).

Additional steady flow confined bank experiments have been completed within meandering flumes, taking into account the predominant planform shape of natural streams. Analyzing flow pattern variation, da Silva et al. (2006) utilized five different sine-generated meandering flumes (initial deflection angles of 30˚, 50˚, 70˚, 90˚, and 110˚) to examine how planform and bed form morphological changes differ. All channels had a consistent width, 40 cm, sediment ($D_{50}$ of 2.2 mm) and number of meanders (2), but the total flow length varied as it is a function of deflection angle. The results showed that each unique deflection angle had its own planform morphological trends and bed form deposition and erosion zone (da Silva et al., 2006).

Binns & da Silva (2009) investigated the time of bed development using a meandering channel having a deflection angle of 70˚; the study consisted of five separate runs with varying flow rates and slopes. The flume was 18 m long, 80 cm wide and consisted of two meander lengths; silica sand with a mean diameter of 0.65 mm was used for the bed. The results from this experiment plus the addition of previous meandering studies (Hasegawa, 1983; Holzwarth, 2006; Termini, 1996) provided the first step towards developing a quantification (equation) of the bed development time (Binns & da Silva, 2009).

Termini & Piraino (2011) analyzed the impact of cross-sectional flow on bank erosion in a 50 cm wide flume with a deflection angle of 110˚, two meander lengths, and a bed made of quartz sand ($D_{50}$ of 0.65...
Two experiments were undertaken, one with high width-to-depth and one with a small width-to-depth ratio. It was found that this cross-sectional flow only occurred in the small width-to-depth ratio scenario (Termini & Piraino, 2011).

Although completed with a smooth rigid bed, the study of shear stress in a meandering channel, completed by Patnaik et al. (2014), provides a research method for future studies. The research was completed using a trapezoidal channel with a deflection angle of 90° and implemented Preston tubes for shear stress measurements (Patnaik et al., 2014). The validity for use of Preston tubes is found in Sin (2010) where the Preston tube method correlated with laboratory data the closest. Contrary to general consensus, Patnaik et al. (2014) found that the higher shear force occurred at the inner bank, but this could be due to the smooth channel and further investigations for roughened channels are required (2014).

A further study was completed by Binns and da Silva (2015) as an extension of their previous work to develop an equation for bed development. The use of two additional 30 cm wide meandering flumes, one with a deflection angle of 45° and another with an angle of 95°, were used in conjunction with data from Binns and da Silva (2009) to quantify the bed development time (Binns & da Silva, 2015).

Similarly, Termini (2015) expanded on Termini and Piraino (2011) utilizing the same laboratory set-up to investigate bed shear stresses. The results of the study show that the curvature affects both the magnitude and direction of the bed shear stress vector, with erosion zones occurring at the outside edges from the curve entrance through the apex before dissipating (Termini, 2015). These results are in direct contrast to the results reported by Patnaik et al. (2014), suggesting bed roughness and a mobile bed, both limitations mentioned by Patnaik et al. (2014), do in fact play a major part in shear stress distribution.

3.1.2 Unsteady Flow and Confined Banks

The analysis of how unsteady flow impacts sediment transport has also been rigorously studied in the past decades. Almost all of the studies have been completed within a straight flume, aside from Yen & Lee (1995) who completed a series of experiments on a channel bend with a radius of 4 m. Table 2 provides an overview of laboratory research undertaken with unsteady flow conditions.
Table 2: Unsteady flow and confined banks research

<table>
<thead>
<tr>
<th>Author</th>
<th>Discharge (m³/s)</th>
<th>Width (m)</th>
<th>Meandering</th>
<th>Slope (m/m)</th>
<th>Sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Sutter et al.</td>
<td>0.0022-0.0402</td>
<td>0.39</td>
<td>N/A</td>
<td>1/333</td>
<td>Sand</td>
</tr>
<tr>
<td>Lee et al. (2004)</td>
<td>0.024-0.084</td>
<td>0.6</td>
<td>N/A</td>
<td>0.002</td>
<td>Sand</td>
</tr>
<tr>
<td>Nelson et al.</td>
<td>0.01-0.02</td>
<td>0.25</td>
<td>N/A</td>
<td>0.002</td>
<td>Sand</td>
</tr>
<tr>
<td>Bombar et al.</td>
<td>0.01-0.09</td>
<td>0.8</td>
<td>N/A</td>
<td>0.005</td>
<td>Gravel</td>
</tr>
<tr>
<td>Guney et al.</td>
<td>0-0.06</td>
<td>0.8</td>
<td>N/A</td>
<td>0.006</td>
<td>Gravel</td>
</tr>
<tr>
<td>L. Wang et al.</td>
<td>0.0008-0.018</td>
<td>0.3</td>
<td>N/A</td>
<td>1/120</td>
<td>Gravel</td>
</tr>
</tbody>
</table>

| Yen & Lee (1995)   | 0.02-0.075       | 1         | Yes        | Deflection Angle = 90° (semi-circle w/ radius = 4m) | 0.002 | Sand |

De Sutter et al. (2001) examined suspended transport loading using trapezoidal unsteady hydrographs (all having the same maximum flow) and varying sediment characteristics. To complement the laboratory experiments, the authors also utilized a field site to investigate the effects of the unsteadiness by creating artificial floods. The results of the study found that the unsteadiness of the flow (unsteadiness parameter) increased transport rates, suggesting that the shortest time to peak causes the most sediment discharge (De Sutter et al., 2001). This result was also observed by a previous study (De Sutter et al., 1999) utilizing strictly non-cohesive sediment. Additionally, subsequent flows provided less transport, suggesting that cohesive riverbeds have stochastic characteristics in which “weak” spots are eroded during the initial flow and the overall bed resistance grows through subsequent flows (De Sutter et al., 2001).

Analysis of unsteady flow effects on bed load transport rates was completed by Lee et al. (2004) through the use of triangular hydrographs. The results of the study showed a delay in the peak sediment discharge from the peak flow rate, this lag time was found to be 6-15% of the total hydrograph duration from the twelve experimental runs completed. This lag was in agreement with previous research (Griffiths & Sutherland, 1977) which suggested the lag time to be 5-10% of the hydrograph duration. Lee et al. (2004)
also found that the measured bed load transport rates during the unsteady events were in excess of the values predicted from steady flow experimental results.

Nelson et al. (2011) observed bed form initiation and development for two simple time-varying flows. The results of the tests saw the development of two-dimensional bed forms, which grew in tandem with flowrate. As the flowrate was lowered back to the original value, the bed forms experienced a decrease in height (flattening), while the wavelengths of the dunes remained the same (Nelson et al., 2011). The researchers also employed the use of a numerical model which generally underestimated bed form evolution. The resulting sediment transport rates were not disclosed as the paper focused solely on bed form evolution.

Utilizing both triangular and trapezoidal hydrographs, Bombar et al. (2011) investigated the unsteadiness parameter and total work flow. Bombar et al. (2011) also observed a lag in peak sediment rates from peak discharge rates, in agreement with previous studies (Griffiths & Sutherland, 1977; Hassan et al., 2006; Lee et al., 2004; Plate, 1994; Reid et al., 1985; Wang, 1994). The development of a new unsteadiness parameter, based on the net acceleration concept, showed a direct correlation with total sediment yield, which would be expected in nature (Bombar et al., 2011); this direct relationship is in contrast to previous unsteadiness parameters used in earlier studies (De Sutter et al., 2001; Lee et al., 2004). The proposed equation from Bombar et al. (2011) is an improvement on previously developed equations as it is more accurate with real world conditions and is supported by both the published and previous research data (Qu, 2002).

Analysis on the effect of bed armouring was completed using a bimodal gravel sand mixture by Guney et al. (2013) with varying antecedent events prior to exposing the flume to a triangular hydrograph. After the antecedent flows, the armour ratio was calculated as the ratio of surface median sediment size to the subsurface median sediment size. A linear relationship between the bed load and the armour ratio was found, one in which lower armour ratio produced higher bed load transport rates (Guney et al., 2013).

Using distributed hydrographs, included a few asymmetrical tests, the interaction between flow properties and temporal discrepancy in sediment transport rates was completed (L. Wang et al., 2015). The experiments were completed with two separate bed conditions, unimodal and bimodal sand beds. Even with the asymmetric hydrographs, the peak sediment transport was found to lag behind the peak flow discharge. However, the researchers broke the bed sediment mixtures into three categories, coarse (> 8 mm), medium (4-8 mm), and fine (< 4 mm), and found that the coarse sediment transport rate peaked on the rising limb or near the peak of the hydrographs, while the finer sediment transport rate peaked on the falling limb (L. Wang et al., 2015). Another major finding from this research was the importance of
medium class of sediment for channel stabilization, as the bimodal mixture experienced higher overall transport rates than the unimodal mixture under the same hydrograph (L. Wang et al., 2015).

Although not a meandering set of curves, the study of bed load through a curve has been undertaken by Yen & Lee (1995) in a 1 m wide channel through a 4 m radius curve. Using five different hydrographs, the authors investigated the changes in the bed topography. The flows with the higher maximum flow and shorter time to peak produced the largest deposition and scour zones; the depositional zone occurred at the inner bank prior to the apex, while the scour zone occurred at the outer bank after the apex of the curve. The large differences in the channel topographies after the experimental runs can be attributed to the unsteadiness parameter, in that a larger unsteady parameter causes more aggressive bed topography adjustments. The point of no change in bed elevation moves outwards towards the outer bank as the unsteadiness parameter increases (Yen & Lee, 1995). The total amount of sediment yield also occurred in the test runs with a higher maximum flow and unsteadiness parameter (Yen & Lee, 1995), the influence of a higher unsteadiness parameter on sediment discharge conforms with previous research discussed above (Bombar et al., 2011; De Sutter et al., 2001).

3.1.3 Steady Flow and Unconfined Banks

In recent years, the development of laboratory facilities capable of simulating unconfined banks have been created. This more natural system allows for planform adjustments in addition to channel bed morphology. The difficulty with analyzing the adjustments of natural single channels in terms of planform sinuosity is due to the inability to acquire appropriate field data (Eaton & Church, 2004), which is the reason laboratory experiments are important in the growth and understanding of this field. The number of studies completed, shown in Table 3, are substantially fewer than those with confined banks.
Table 3: Steady flow and unconfined banks research

<table>
<thead>
<tr>
<th>Author</th>
<th>Discharge (m³/s)</th>
<th>Width (m)</th>
<th>Meandering</th>
<th>Slope (m/m)</th>
<th>Sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schumm &amp; Khan (1972)</td>
<td>0.00425</td>
<td>0.305-1.71</td>
<td>No Straight with initial bend (40°)</td>
<td>0.001-0.002</td>
<td>Sand</td>
</tr>
<tr>
<td>Eaton &amp; Church (2004)</td>
<td>0.0026-0.0043</td>
<td>0.4-0.65</td>
<td>No Straight with initial bend (25°)</td>
<td>0.0109-0.013</td>
<td>Gravel</td>
</tr>
<tr>
<td>van Dijk et al. (2012)</td>
<td>0.001</td>
<td>6</td>
<td>N/A</td>
<td>0.0055</td>
<td>Sand</td>
</tr>
<tr>
<td>Luzi (2014)</td>
<td>0.0016-0.0034</td>
<td>0.34</td>
<td>Straight with initial bend (25°)</td>
<td>0.016</td>
<td>Sand</td>
</tr>
<tr>
<td>Van de Lagewag et al. (2014)</td>
<td>0.001</td>
<td>6</td>
<td>N/A</td>
<td>0.0055</td>
<td>Sand</td>
</tr>
<tr>
<td>Song et al. (2016)</td>
<td>0.0001-0.0014</td>
<td>0.1-0.2</td>
<td>Deflection Angle 30-60°</td>
<td>0.005</td>
<td>Sand</td>
</tr>
</tbody>
</table>

Schumm & Khan (1972) attempted to develop a meandering channel from an initial straight channel under varying entrance conditions, noted as straight entrance, initiating bend, and suspended sediment load with initiating bend. Each condition had multiple tests completed under varying longitudinal bed slope conditions, while holding constant the discharge in all tests. The initial straight channel remained straight in response to the discharge until the slope steepened (0.004 m/m), highlighting that exceeding a threshold slope causes meandering tendencies (Schumm & Khan, 1972). Utilizing an initial bend prior to the straight channel, Schumm & Khan (1972) measured the development of the channel and thalweg sinuosity through various slopes; the findings show that sinuosity increased as slope increased and the thalweg sinuosity was always greater than the channel sinuosity (Schumm & Khan, 1972).

Eaton & Church (2004) examined channel stream morphology using a stream table to investigate how equilibrium is achieved. As experienced in previous studies utilizing a stream table (Schumm & Khan, 1972), the meandering thalweg channel isn’t a truly meandering channel, but it does provide valuable
insights. Eaton & Church (2004) noted that the primary adjustable variable throughout the experiments was the channel slope and the resulting channel thalweg experienced bed armouring throughout time.

The use of a 11 m long, 6 m wide flume at Utrecht University was undertaken by van Dijk et al. (2012) to examine the evolution of a meandering channel planform pattern. An initial straight channel was created in the flume and allowed to develop over a 30 hour period. After the 30 hour development time, the location of inflow, both sediment and water, moved laterally to the left at a constant rate of 1 cm/hr for 50 hours and then constantly to the right at a constant rate of 1 cm/hr for 160 hours until the end of the test. The movement of the inflow location caused the channel to continually adjust, causing a dynamic meandering channel. The experiment highlighted the development and interactions of chute cutoffs, point bars, and meander growth in a river floodplain.

The development of a 2D numerical model was undertaken to accurately model channel morphology with a comparison to both a laboratory flume and a real world reach (Asahi et al., 2013). The laboratory study utilized in the numerical model comparison was completed by Shimizu et al. (1995) and consisted of a single sine-generated meander planform followed by a straight channel that could grow laterally and two steady flow conditions were inputted, one as bank full and the other as a low flow. The resulting high flow model displayed moderate amplitude meanders migrating downstream, while the low flow model showed a nearly straight channel with alternating bars (Asahi et al., 2013). The computer model also examined cyclical hydrographs shifting between the high and low flow discharges, the results of these hydrographs produced a similar planform shape to natural meandering rivers (Asahi et al., 2013). The developed model succeeded in capturing channel sinuosity evolution and width growth; the resulting planform models were in agreement with Pizzuto’s (1994) field observations on the meandering Powder River (Asahi et al., 2013).

Luzi (2014) continued research initiated by Eaton & Church (2004), investigating the channel stability and sediment transport using a steam table. Across the nine experimental runs, the general trend was an under-representation of the largest size sediment in transport and the introduction of sediment feeding didn’t result in aggradation through the flume (Luzi, 2014). The adjustment of the channel to the flows was found to primarily be in the formation of bed forms (pool, riffle structure) as opposed to the bed surface grain size redistribution. The results of this are in conflict of the findings of Eaton & Church (2004), as Luzi (2014) noted the armouring channel bed texture tended to be a short term response. Greater sediment transport rates were noted during the runs with higher flows and/or finer grain distributions in the sediment feed (Luzi, 2014).
Van de Lageweg (2014) use the same experimental apparatus and set up as van Dijk et al. (2012) to examine the development of point bars in a meandering channel. The results of the experiment found that the erosion of the outer bank at the meander apex provided the sediment for point bar deposition at the inner bank. Providing sediment pulses at the flume inlet did little to increase sediment deposition and point bar growth. This suggests that channel widening is necessary for point bar formation (Van de Lageweg et al., 2014).

The development of a continuously meandering channel was produced to investigate fluvial processes by adjusting the channel width and flow rate (Song et al., 2016). Seven experimental runs were completed with varying sinuosity, discharge, and channel width; the sinuosity was based on an initial deflection angle that varied from 30’ to 60’. Observations from the experiments showed that the outer banks are eroded more quickly than the inner banks and that the runs with greater discharge conditions had the tendency to straighten the meandering channel (Song et al., 2016). The transport rates of the sediment was found to initially increase as the banks eroded before decreasing as the bed developed and armouring occurred. Song et al. (2016) also found the sediment transport rate to be very sensitive to discharge flow rate, while increases in discharge resulted in quick bed form adaptation (pools and point bars) depending on the maturity of the structures.

### 3.1.4 Unsteady Flow and Unconfined Banks

A continuation on the previous section, analysis of a laterally unconfined system under unsteady events is required as this is more representative of the processes in natural systems. Unfortunately, very little research has been completed within this area; most of the completed research has focused on qualitatively evaluating natural riverine systems and little to no previous research exists on modelling or physical laboratory studies. The only previous physical research completed with unsteady flow on a totally unconfined channel was completed by van Dijk et al. (2013); a synthesis of their research conditions is found in Table 4. Additional physical studies published investigate submarine sinuous channels (Janocko et al., 2013; Straub et al., 2011), which are outside the scope of this research.

<table>
<thead>
<tr>
<th>Author</th>
<th>Discharge (m³/s)</th>
<th>Width (m)</th>
<th>Meandering</th>
<th>Slope (m/m)</th>
<th>Sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>van Dijk et al. (2013)</td>
<td>0.00025-0.0005</td>
<td>0.15</td>
<td>N/A</td>
<td>0.01</td>
<td>Sand</td>
</tr>
</tbody>
</table>
The flume and experimental setup of van Dijk et al. (2013) was similar to previous laboratory configurations in earlier research (Van de Lageweg et al., 2014, 2013; van Dijk et al., 2012) but a step hydrograph was implemented instead of a steady flow. The hydrograph ran at bank full conditions for two and a half hours before increasing to above bank full for the final 30 minutes of the test. Two experimental runs were completed, with the only difference being the amount of cohesive soil in the sediment feed at the flume inlet. The first run without any cohesive sediment in the sediment feed caused the channel to develop into a braided network as the channel shifted with the changing inlet location (van Dijk et al., 2013). However, the presence of the cohesive soil in the sediment feed during the second experimental run reduced erosion rates by 50% and increased bank stability. This increase in bank stability caused an increase in sinuosity as the meanders grew and the stability reduced chute cutoffs creating a continuous single thread channel (van Dijk et al., 2013).

Field investigations are important as they provide the opportunity to verify the scientific results obtained within a laboratory study. Eaton & Lapointe (2001) examined two flood events (7-year and 275-year events) on the Sainte Marguerite River to determine the morphological response of the river and to estimate the sediment transport during the flooding events using the Meyer-Peter & Muller equation. Using a straightforward conservation of sediment equation, the results of the anticipated bed morphological changes gave reasonable results; the results were more consistent for the 7-year event, however, the method may still be applicable for larger events (Eaton & Lapointe, 2001). Similarly, it was found that the use of the Meyer-Peter & Muller equation in conjunction with an event index produced adequate results and the authors suggested applying this method to further data sets to validate its applicability.

Analysis on the applicability and validity of existing bed load transport theorems was undertaken and analyzed against a range of field data sets and flume data (Recking et al., 2012). The results of the research showed that most of the transport equations were effective at predicting the results obtained in the laboratory, but all were subjected to severe limitations with the field data; once \( r^* < 2 \), most bed load formulas were no longer valid. The longer the field measurement period, the more accurate the results of the bed load equations, especially when used in their validity zone (Meng et al., 2016; Recking, 2010; Recking et al., 2012; Talukdar et al., 2012).

As discussed in the previous section, Asahi et al. (2013) implemented cyclical hydrographs between the high flow and low flow within their model and produced qualitatively similar planform patterns to those of real rivers in the world.
Thompson & Croke (2013) investigated geomorphic effects of a large magnitude storm event on a reach in eastern Australia. The reach is initially confined by bedrock before exiting to a sinuous planform in the unconfined floodplain. Analysis of the geomorphological changes was completed using airborne LiDAR, comparing pre and post DEMs. The result of the large storm event saw extensive lateral erosion and channel widening in the upstream confined section, but negligible widening was experienced in the unconfined section where sediment aggradation occurred (Thompson & Croke, 2013).

Analysis of the planform morphological changes of the Taro River in northern Italy over a 183 year period was undertaken using maps and orthophotos (Clerici et al., 2015). The results of the investigation found that the channel length and river sinuosity regularly grew over time, while a continuous reduction in channel width was observed. The largest increases in channel length and sinuosity occurred in the same timespan as the largest decreases in average channel width. The evolutionary trends and results reported by Clerici et al. (2015) are valuable in providing a comprehensive review of river dynamics in nature over a long period, as these real world time-steps can be produced in a laboratory setting at a much quicker rate.

3.1.5 Summary

As can be seen, there have been numerous experimental studies investigating bed load transport and morphological changes. Some of these studies, although slightly outside the scope of this thesis, provide a good background into the processes in natural systems. Combining all this research into a cohesive model would provide a comprehensive catalog for better understanding and modelling a real world river reach. The focus of the present research is on developing a better understanding of sediment transport rates and morphological development for an unconfined meandering channel. The abundance of research on confined banks show that there is still great uncertainty on this topic, as previous studies have been primarily focused on very narrow research areas. The lack of previous research on unconfined banks show that much work must be done in this area in the coming years to ensure that research completed on unconfined banks complements confined banks studies. Patnaik et al. (2014) even mention in their future recommendations that, “experiments on mobile bed are preferred to substantiate the knowledge on channel migration pattern and sediment studies” (p. 167). Similarly, Duan & Julien (2010) note the limited experimental data for flow and sediment transport in unconfined meandering channels. This thesis is believed to be the second study (van Dijk et al., 2013), in a laboratory case, to investigate unsteady flow and unconfined banks.
The equations used in the development of the meandering channels also varied, most previous research (Binns & da Silva, 2009, 2015; da Silva, 2006; Song et al., 2016; Termini, 2015; Termini & Piraino, 2011) followed the equations developed by Leopold & Langbein (1966) and Langbein & Leopold (1966). However, the two studies involving deflection angles of 90° (Patnaik et al., 2014; Yen & Lee, 1995) didn’t reference any unique equations.

3.2 Photogrammetry

Conducting morphological measurements after every time-step is important in quantifying the bed form and planform adjustments to the flow. Many different application and technology are available to accomplish this. Some of the most common are laser scanners, LiDAR, and sonar scanners (Yager et al., 2015); however, these methods often require expensive equipment and expertise (Micheletti et al., 2015a, 2015b; Morgan et al., 2017; Mosbrucker et al., 2017). Another option is completing manual measurements, but this is very time consuming and subject to human error. The recent alternative of photogrammetry has become feasible as an alternative, which utilizes photography to acquire 3D data. The use of consumer grade cameras without prior expert knowledge makes it ideal for many different applications (Micheletti et al., 2015b). By stitching together the 2D images, an accurate 3D model can be created using photogrammetry software.

The use of photogrammetry within a laboratory flume setting has been undertaken in several previous studies (Butler et al., 2002; Chandler et al., 2000; Morgan et al., 2017). Chandler et al. (2000) found that the accuracy of photogrammetry across different flume scales was very good and the process time was quite short. Chandler et al. (2000) set out to quantify the accuracy of a photogrammetry created DEM against direct measurements from one of the flumes and found the correspondence to be excellent with an accuracy of 1.9 mm. It should be noted that all photogrammetry tests completed in the laboratories utilized ground control points on the flume edges to provide accurate coordinates for comparison purposes. The control points also assist with stitching together the overlapping photo pairs. Morgan et al. (2017) has provided the most comprehensive analysis of photogrammetry in a flume setting and developed a general set of guidelines for photogrammetry use in future flume studies. Utilizing five different flumes of varying size and two different software packages, Agisoft PhotoScan (proprietary software) and VisualSFM (public domain software), the researchers compared the accuracy to that of two laser scanners. The authors found that the photogrammetry techniques produced similar results to that of the laser scanner in a much shorter time and that the Agisoft PhotoScan software performed better than
the VisualSFM, including producing point clouds with nearly twice the density (Morgan et al., 2017). Looking specifically at the Agisoft software, many quality options are available for selection throughout processing; as the accuracy settings are increased, so too is the processing time. It was found that using the “medium” and “high” settings produced adequate point cloud generation and adequate elevations (median accuracy of 0.001m) when compared to the “highest” and “ultra high” settings that produced elevation accuracies of 0.000m, but computing times increased from hours to days. The researchers also examined how the photo distances and angles impacted the Agisoft results. The distance didn’t impact the topography by more than one millimeter, while the 60% angle shot performed better at further distances; however, grain size delineation was much more pronounced at the closer shots (Morgan et al., 2017). The overall findings of Morgan et al. (2017) show that photogrammetry can produce topographical point clouds with greater point density and comparable accuracy to laser scanners within a flume setting at a reduced cost and with less processing time.

The use of photogrammetry for bed sediment distribution has been utilized in previous studies (L. Wang et al., 2015) with Sedimetrics software, while other authors highlight the difficulty of using photogrammetry to develop a bed grain size distribution (Yager et al., 2015) with respect to camera perspectives and lighting amongst other factors. Shim & Duan (2017) utilized image capture to analyze bed load transport through a flume with promising results. Morgan et al. (2017) describe the detail required for grain scale topography delineation as a factor of the camera sensor resolution and focal length, with a recommendation of adjusting the camera distance until 100 pixels per grain is achieved. The applicability of photogrammetry use for field level sites was also highlighted by a few of the researchers (Chandler et al., 2000; Marteau et al., 2017; Micheletti et al., 2015a, 2015b; Mosbrucker et al., 2017) and could also be implemented with historical photos (Bakker & Lane, 2017). Also of interest is the ability for DEMs developed from photogrammetry to be used in hydraulic modelling software to predict geomorphic adjustments to the channel (Marteau et al., 2017); this has been completed in a few previous studies using field level sights and implementing the numerical models DELFT3D-FLOW (Javernick et al., 2016) and River2D (Tamminga et al., 2015), respectively.

3.3 Computer Modelling (HEC-RAS)

The use of computer modelling is prevalent in hydraulic engineering as it can solve the iterative steps within a relatively short time. One of the most common open source software packages is the
Hydrological Engineering Center’s River Analysis System program (HEC-RAS). HEC-RAS can perform computations on the hydraulics of flow and sediment transport capacity.

Two of the equations listed above in the transport equation section, Meyer-Peter & Muller and Engelund & Hansen, are available for use in the software package. Brunner & Gibson (2005) highlight the development of the sediment transport capacity capabilities developed for HEC-RAS, including the transport capacity and the mobile bed routing. The program uses quasi-steady hydrodynamics to solve for the sediment transport and adjusts the bed at the end of each time-step; since the experiments completed in this research were already utilizing steady or quasi-unsteady hydrographs, this method is adequate. A control volume at each cross section is implemented by HEC-RAS to calculate the sediment transport equations (Brunner, 2010, 2016b). Adjustments to the bed can be calculated within the software, but a simple uniform aggradation or degradation is applied across the channel bottom (Brunner, 2010; Brunner & Gibson, 2005), so bed form analysis cannot to be examined. The bed change is calculated within the model as a wedge of sediment evenly distributed across the cross section with the appropriate mass/volume to the calculated surplus or deficit from the transport equations (Brunner, 2010). In addition to the bed elevation adjustments, HEC-RAS also calculates the bed surface sediment distribution and its adjustment through time. Two methods of bed sorting and armouring are available in the model, the Exner 5 and the Active Layer Method. The Exner 5 method was developed by Thomas (1982) and assumes two portions within the active layer for sediment transport. These two portions are the cover layer and the subsurface layer which allows for bed armouring within the cover layer. In contrast, the Active Layer Method simply employs one total layer for the active layer, estimated as the $D_{90}$ of the bed sediment. The Active Layer Method is described as only being appropriate for gravel beds (Elsayed, 2013). HEC-RAS uses fall velocity to determine the boundary between bed load and suspended transport. Multiple equations are available within the program for determining the fall velocity, including the Rubey method. The Rubey equation has been found suitable for sands and performs best with crushed quartz grains (Brunner, 2010, 2016b).

Elsayed (2013) provides a general procedure for completing the sediment analysis within the HEC-RAS software including the initial definition steps. The geometry data required for HEC-RAS will be completed using HEC-GeoRAS to convert the DEM data created by AgiSoft Photoscan into an appropriate format. The conversion of the DEM requires the intermittent use of ArcGIS. Once the DEM is opened in ArcGIS, HEC-GeoRAS will be utilized following the procedure of Ackerman (2009). Subsequent steps within the HEC-RAS procedure will follow those outlined by Elsayed (2013).

The results obtained from HEC-RAS sediment transport analyses have provided accurate results in comparison with other modelling software and laboratory flume studies (Brunner & Gibson, 2005).
Previous studies without calibration data found that the sediment model is highly sensitive to the selected transport function equation and the incoming sediment grainsize gradation (Miller et al., 2015).
Chapter 4: Methodology

4.1 Laboratory Facility

The flume utilized in this research was constructed in the University of Guelph’s Water Resources Engineering Laboratory. The frame of the flume was constructed before sheet metal was screwed into the frame; the sheet metal was overlapped and sealed with silicon. A custom polyethylene liner was constructed to fit over the sheet metal and the head and tail tanks. The liner was loosely fit in the flume and then secured once caps were screwed into the frame through the liner. Since the floor in the lab is sloped to drain excess water, the caps were held level across the flume. An existing reservoir and recirculating water system in the lab was utilized to provide water to the flume. As such, new piping tied into the existing pipe leading to an existing acrylic walled flume. The sand flume itself consisted of three main sections: the headwater tank, flume basin, and the discharge tank. A sheet metal baffle separates each section. The baffles have a cutout so weir plates of varying widths and elevations can be installed. The flume basin has dimensions of 5.6m x 1.9m. An overview schematic of the laboratory set up is seen in Figure 3. Additional schematic details are seen in Appendix B.

4.2 Channel Geometry

The initial deflection angle for the present sine-generated laboratory channel was 70°. The generation of the channel geometry was completed using an Excel file solving the equations derived by Leopold & Langbein (1966) and Langbein & Leopold (1966).

For a deflection angle of 70° and a channel width of 30 cm, it was calculated that a maximum of two full meanders could fit within the basin dimensions. This also allowed for a straight approach and exit sections between the meanders and the weirs to reduce the impacts of the weirs on the flow. The straight sections were 0.9m in length at both the inlet and outlet.

The corresponding x,y bank lines (inner and outer) output from Excel were converted into a comma delimited (csv) file for import purposes to AutoCAD. The SPLINE command was used in AutoCAD to import the x,y csv file. Once in AutoCAD, the linework was scaled up to the real life size required. The real life scaled channel outline was plotted to scale (1:1) on 36” x 60” paper size. The printed half meander channel was cut out and traced onto hardboard, then the hardboard was cut out.
To ensure the valley slope of the channel was consistent throughout the flume, the exit valve was closed and the flume was allowed to fill slowly. A chalk line was utilized on the flume wall to delineate the sand level. As the water rose, adjustments to the sand bed were completed to ensure the water level remained consistent across the width of the flume and the sand was level with the chalk line. This method achieved a uniform valley slope; it also consistently saturated and consolidated the sand material in the flume basin. The exit valve was opened slightly to allow the water to slowly drain without displacing the surface material.

The hardboard cutouts of the stream planform geometry were placed on the flume bed and measured off of the wall and against each other to ensure the channel width was 30 cm throughout the half meander. A manufactured carving tool was used to dig out the sand between the hardboard cutouts. The carving tool was a piece of sheet metal in the shape of a “T” with the bottom stem being bent 90˚ at a point half way down the sheet. This allowed the top part of the tool to rest on the hardboard while being dragged through and the bent portion of the stem acted as a shovel.

The overall slope of the channel was governed by the inlet and outlet weir elevations. During the carving process, measurements were taken at the apexes to ensure that the appropriate amount of elevation drop occurred according to the prescribed slope. Measurements were taken from the level caps. A pair of hand levels were used to ensure that the longitudinal bed slope continuously and consistently dropped along the entire length of the channel. It is assumed that the radial slope in the channel is zero, i.e. the bed is flat.

Water was pumped from the reservoir to a constant head tank before entering the channel. A discharge tank at the channel end allowed for sediment to be captured with the sediment catch (Figure 44) before returning to the reservoir. A schematic of the laboratory set up and equipment used is shown in Figure 3.
4.3 Sediment

Multiple sediment samples were obtained from local suppliers to determine their suitability for use in the present experiments. Samples were obtained from Lafarge Aggregates, F. E. Prior, and Guelph Building Supplies in the city of Guelph, Ontario. The concrete sand samples were determined to be the most applicable for use in the present thesis, as the $D_{50}$ and the distribution of the concrete sand was best suited for the flow discharges in the experiments.

The flume basin was filled with sand donated from Lafarge Aggregates in Guelph. The material was a concrete sand with a $D_{50}$ of 0.85 mm; gradation information is found in Table 21 in the Appendix. This nominal particle diameter with a shape factor of 0.5 produces a spherical fall diameter of 0.75 mm. The concrete sand comes from the Lafarge Cambridge pit, where it is extracted, screened, and washed. The material is unimodal in nature and consists of predominantly medium to small sized sand grains; fines and gravel portions were at a minimum. Figure 4 shows the material gradation; the bars refer to the percent retained (primary vertical axis) and the line refers to the percent passing (secondary vertical axis). The material is also non-cohesive in nature. The specific gravity ($\gamma'$; Eq. 16) of the sand was measured to be 2.501. The specific weight for the sediment was calculated as 24534.8 N/m$^3$. 

Figure 3: Experimental facility schematic (all dimension in meters) (flow is from left to right)
4.4 Experimental Set-up

Three tests were completed with varying flow conditions; two were steady flow and the final test was a quasi-unsteady flow. The Yalin sediment transport equation was utilized in the development of the experiments for this research to approximate the amount of bed load transport anticipated. The kinematic fluid viscosity is assumed equal to $1.006 \times 10^{-6}$ m²/s for the duration of the experiments. The specific weight for water is 9810 N/m³. The flow regime within this research was turbulent flow.

During the experiments in this research, the roughness Reynolds Number was in the range of 56 to 67. The roughness Reynolds Number was 56 for Experiment A, 62 for Experiment B, and varied from 56 to 67 during Experiment C. Experiments A, B, and C, will be henceforth referred to as EXP A, EXP B, and EXP C, respectively. The use of the shape factor for the sand utilized in the experiments decreases the mean sphere diameter and thus decreases roughness Reynolds Number. This decreases to 49, 54, and 49-60. The experiments completed in this research were designed such that no wash load occurred and the flow was to remain in the exclusive bed load transport zone, with the relative tractive force held between 2.5 and 4 (refer to Eq. 5 in Chapter 2). It is assumed that the only mode of sediment transport within these experiments is via bed load. Reynold’s Number scaling was not used in this research. The longitudinal bed slope is used to define the energy grade line as uniform flow is assumed throughout the experiments (slope of the energy grade line is equal to the bed slope).
During the experimental runs, the width to depth, or aspect, ratio \( \frac{B}{h} \) was maintained above the value of 10. This is considered a wide channel. Using 10 as the differentiator for a “wide” channel is in accordance with other authors (Binns & da Silva, 2015; da Silva et al., 2006; Ebrahimi, 2015; Termini, 2015; Termini & Piraino, 2011; Yalin, 1992). “Wide” channels simplify the flow conditions and assume no secondary flows occur across the cross sections.

No sediment was supplied to the flow during the experiments (i.e., no sediment feeding), as such, an attainable equilibrium condition could be achieved. In this regard, the tests are similar to the tests completed by Chen et al. (2017), with equilibrium conditions occurring after an initial sorting phase once the discharge was introduced. Table 5 and Figure 5 summarize the hydraulic conditions for each experimental run and the corresponding hydrograph for the discharge condition, respectively. The volumetric flow is measured at the inlet pipe with a transit time ultrasonic meter. The flow meter is valid for flow velocity between 0.03-12 m/s, well within the designed flows, with an accuracy of ± 1% (Dynasonics, 2008). Minor variation in discharge occurred across the ten minute time-steps, therefore, measurements were taken every minute and averaged over the ten minute time-step duration. The maximum fluctuations in the actual flow versus the designed was ± 6.4%. The use of an acoustic Doppler current profiler in the channel was attempted, but the flow depths were too shallow to obtain accurate flow velocities. Sediment was collected at the discharge tank at the end of each time-step to be further quantified and analyzed. The channel averaged flow depth was measured by hand with a ruler at the three apex positions of the meandering channel. The label for each apex is shown in Figure 6. Measurements were taken at the channel centreline and measured to an accuracy of 0.1 cm. Table 6 highlights the measurement times for each experimental run.

Table 5: Summary of experimental hydraulic conditions

<table>
<thead>
<tr>
<th></th>
<th>EXP A</th>
<th>EXP B</th>
<th>EXP C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q (L/s)</td>
<td>0.7988</td>
<td>1.1094</td>
<td>0.7885-1.4564</td>
</tr>
<tr>
<td>h (cm)</td>
<td>2.05</td>
<td>2.5</td>
<td>2.0-3.0</td>
</tr>
<tr>
<td>S (m/m)</td>
<td>1/185</td>
<td>1/185</td>
<td>1/185</td>
</tr>
<tr>
<td>Re*</td>
<td>56</td>
<td>62</td>
<td>56-67</td>
</tr>
<tr>
<td>Fr</td>
<td>0.289</td>
<td>0.294</td>
<td>0.289-0.297</td>
</tr>
<tr>
<td>Re</td>
<td>9,382</td>
<td>12,416</td>
<td>9,382-16,054</td>
</tr>
<tr>
<td>( \eta^* )</td>
<td>2.386</td>
<td>2.896</td>
<td>2.386-3.475</td>
</tr>
<tr>
<td>( B/h )</td>
<td>15</td>
<td>12</td>
<td>10-15</td>
</tr>
</tbody>
</table>
Table 6: Measurement times of morphological changes and sediment transport in each experiment

<table>
<thead>
<tr>
<th>Measurement Times (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP A</td>
</tr>
<tr>
<td>0 10 20 30 40 50 60 90 120</td>
</tr>
<tr>
<td>EXP B</td>
</tr>
<tr>
<td>0 10 20 30 40 50 60 90 120</td>
</tr>
<tr>
<td>EXP C</td>
</tr>
<tr>
<td>0 30 40 50 60 70 80 90 100 110 120 130 140 150 180</td>
</tr>
</tbody>
</table>

The longitudinal bed slope selected for the experiments outlined in Table 5 is similar to a real life reach in New Zealand (Williams et al., 2016). The roughness Reynold’s Number (Eq. 3) is below the fully rough turbulent flow threshold (70), but is firmly within the upper end of the acceptable 40-70 range for flume experiments (i.e., transitional regime of turbulent flow).

![Figure 5: Measured hydrographs of each experimental run](image)

Sediment was dried overnight in the Soil Mechanics Lab and then gradation tests were completed on the dried sediment. No prewashing of the sediment samples was completed as little fines existed in the sand.
4.5 Photogrammetry (Agisoft PhotoScan)

After creating the initial channel and after each time-step, a comprehensive set of photos of the flume were taken for photogrammetry purposes. A Canon EOS Rebel T6i equipped with a Canon EF-s 24 mm prime lens was used for photograph capture. The shutter was set to 1/40, F-stop was held at F/11, while the ISO was allowed to vary. The channel was allowed to drain so no standing water was present during the photography process. This ensured no refraction impacts from the water would occur. The impact of through water photos on DEM development has previously been investigated by Butler et al. (2002). 16 stations around the flume were utilized for complete coverage and repeatability. A step ladder was used to take the photos from a higher vantage point, as recommended by Morgan et al. (2017). Six control points were placed on the flume for accurate coordinate positioning. The control point markers were downloaded from Agisoft, which allows for them to be auto-detected in the software, and were placed so as to box in the channel. Manual measurements for the control markers coordinates were conducted (Table 7). The location of the control points on the flume is seen in Figure 6 (the flow through the flume goes from right to left).

Table 7: Coordinates for the six control points

<table>
<thead>
<tr>
<th>Control Point</th>
<th>X Coordinate (m)</th>
<th>Y Coordinate (m)</th>
<th>Z Coordinate (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>500.000</td>
<td>500.000</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>502.700</td>
<td>500.000</td>
<td>0.000</td>
</tr>
<tr>
<td>6</td>
<td>505.000</td>
<td>499.990</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>500.000</td>
<td>501.956</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>502.700</td>
<td>501.956</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>503.500</td>
<td>501.956</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Verification of the accuracy of the photogrammetry was completed with a preliminary experiment in the flume. Manual measurements were conducted to obtain the bed elevation values and corresponding plan location values across multiple cross sections. The results were compared to a model produced from the Photoscan software with the measured elevation (z) values appearing in the model within a square centimeter of the measured plan (x,y) position. A validity test for a second photogrammetry software was also attempted. Autodesk ReMake, an updated package of Autodesk 123D applied by Micheletti et al. (2015), was used to model the same preliminary experiment; however, the outputted results were inaccurate and scattered.

During the validity procedure with PhotoScan, RAW image files were tested against JPG file format. The RAW file sizes were three-to-four times larger than the JPG files, which increased the processing time; however, the results from PhotoScan using the RAW files were very similar to the results using the JPG file format. This was also noted by Morgan et al. (2017), and as such, JPG photos were used throughout the analysis in this thesis.

Agisoft PhotoScan Professional Edition (Version 1.3) was used for the development of the DEMs. The procedure used with Photoscan followed the recommendations of Morgan et al. (2017) and the user’s manual (Agisoft LLC, 2017). The overlap requirements, from Agisoft (2017), of 60% horizontal and 80% forward to remove “blind-zones” corresponded to around 85 photos for the flume. The photosets at the measurement times were generally 125-150 photos, around 1.5 times the minimum suggested value. Default settings for tie points were used along with “highest” alignment accuracy and “medium” dense cloud quality. Initially, all photos taken for the given time-step were uploaded into a single “chunk” in the software. Estimation of image quality, such as vague photos or poorly focused photos, was completed. PhotoScan compares the contrast between pixels to determine the images quality, assigning each photo a value between zero and one (Agisoft LLC, 2017); photos with a quality of less than 0.5 were deleted.
These photos were often blurry or out of focus. Since the control points were downloaded from Agisoft, the next step was to detect markers and align the photos for each chunk. Once the control points were detected in more than two frames (photos), the software algorithm placed dummy markers at the location of the control point in subsequent photos that weren’t previously detected. Occasionally, the software failed to detect a control marker and manual placement was required. A manual review of all the markers for each chunk was completed; any dummy markers that were visibly placed correctly were confirmed as valid. This updated the algorithm in the software each step and helped reduce the error in the final DEM. The goal was to achieve at least ten valid markers for each control point in each chunk. Another goal was to have valid control points in the highest quality images and images with at least three control points. Target 8, in the top right corner of the flume, had the fewest valid control points because of the flume geometry, camera locations, and channel location. Once all the control points were validated, any photos that were not originally aligned in the first batch process were individually aligned. The hand measured control point coordinates were imported into the software next, this ensured all the chunks would have the same location and line up with each other. The subsequent step was to optimize the aligned photos then proceed with building the dense point cloud. The dense point clouds for each chunk were reviewed before building the DEM and exporting the file. A review of the steps used for DEM generation in Agisoft Photoscan is listed below in Table 8.

Table 8: Steps in DEM production for Agisoft PhotoScan

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Import photos from each time-step into an individual chunk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2</td>
<td>Estimate image quality, delete photos with a quality less than 0.5</td>
</tr>
<tr>
<td>Step 3</td>
<td>Batch process (detect markers and align photos)</td>
</tr>
<tr>
<td>Step 4</td>
<td>Manually validate control point markers</td>
</tr>
<tr>
<td>Step 5</td>
<td>Realign any unaligned photos</td>
</tr>
<tr>
<td>Step 6</td>
<td>Import reference coordinates for control points</td>
</tr>
<tr>
<td>Step 7</td>
<td>Batch process (optimize alignment and build dense cloud)</td>
</tr>
<tr>
<td>Step 8</td>
<td>Build DEM and export TIFF file</td>
</tr>
</tbody>
</table>

The batch processes were completed for all chunks within the experiment and ran continuously until completed. The computing time required for each chunk was about 14 hours depending on the number of photos in the chunk. The largest computing time was for dense cloud generation (around 8 hours), aligning the photos (4 hours), marker detection (1 hour), and estimation of image quality (30 minutes). Additionally, a couple of hours of manual work regarding the control points were needed for each chunk. Figure 7 shows the aligned photos, control points, and dense point cloud for a single time-step (a) and all
time-steps in an experiment (b). As is seen in (b), all control points line-up across all time-steps, ensuring that accurate comparison between time-steps is viable.

Figure 7: Aligned photos and dense point clouds from Agisoft PhotoScan: a) individual time-step (EXP B at 120 min); b) overlay of all time-steps in an experiment (EXP B)

4.6 ArcGIS

The TIFF files produced from Photoscan were imported into ArcGIS (version 10.3.1) for analysis. A mask for the flume basin was developed and data outside was deleted. Figure 8 shows the TIFF file after
the mask delineation; the locations of the point bars and pools in the channel can be clearly distinguished. Delineation of the banks was manually completed for each time-step by tracing polylines along the upper edge of the bank. Manual delineation of the channel features (banks, centerline, thalweg) has been completed in previous studies (Thayer & Ashmore, 2016). Centerline for each time-step was identified using the “polygon to centerline” toolbox add on; the polygon consisted of the two bank lines. “Stack profile” was used to measure the slope within the channel as well as the cross-sectional development at various cross-sections along the length of the channel. The shape files necessary for the cross-sectional analysis were developed using AutoCAD Civil 3D.

![Figure 8: Example of DEM TIFF file in ARCGIS (EXP C, time-step 14)](image)

4.7 HEC-RAS

To complete the hydraulic modelling component, HEC-RAS (version 5.0.3) was utilized. HEC-RAS was chosen as it is a common hydraulic model that is widely accepted in academics and in practice. Unfortunately, HEC-RAS currently is incapable of performing sediment transport for two dimensional flows (Brunner, 2016a). As such, one dimensional sediment transport within HEC-RAS version 5.0.3 will be utilized. The DEM data produced from Agisoft PhotoScan is inputted into the hydraulic model (Marteau et al., 2017). Similar undertakings of coupling Structure from Motion photogrammetry with hydraulic models have been completed in previous studies (Javernick et al., 2016; Tamminga et al., 2015).

HEC-GeoRAS was utilized as a link between ArcGIS and HEC-RAS. The program is able to convert shape files and raster information from GIS into a HEC readable format. HEC-GeoRAS 10.2 was downloaded from the HEC website and added into the ArcGIS software. The user’s manual (Ackerman,
2009) was consulted to ensure appropriate procedure. The required surface information was chosen as “grid” with the initial surface (0 min tiff file). The required stream centerline was chosen as the time 0 centerline and the required cross sections were created every 0.5 m. The optional bank lines were selected, as were the flow path lines. The flow path lines were created using the same steps as the channel centerline, except the enclosed polygon featured the bank line and centerline. For example, the left flow path was calculated as the middle between the left bank line and the channel centerline. The files were then exported from ArcGIS for use in HEC-RAS.

HEC-RAS was used to complete a computer modelling analysis for comparison with the physically measured data. The data obtained from HEC-GeoRAS was imported into geometry plan. Smoothing of the cross-sectional data was required because of rounding issues with HEC-GeoRAS; multiple elevation (z) values occurred at the same plan position in the cross-section. Cross section interpolation was completed in the geometry editor for the length of the reach. A maximum distance between each cross section was chosen as 0.05 m and the cross sections were selected to be perpendicular to the channel centerline to ensure the banks followed meandering pattern. A Manning’s roughness coefficient is also required within the software; a value of 0.03 was selected for both channel and overbank sections as the material in the flume was homogeneous throughout.

Due to an issue with the bank modelling, the geometry file had to be updated with manually inputted cross sections. This ensured the bank lines remained in the correct position throughout reach. Only the data for the first and last cross sections data were manually inputted using measurements from the flume. Cross sections were once again cut perpendicular to the centerline and at a maximum spacing of 0.05 m. This method also resolved an additional problem pertaining to the channel slope in the model. Due to the rounding errors with HEC-GeoRAS, some sections of the reach were flat while others were steep. The updated geometry file now had a consistent longitudinal bed slope. Figure 9 shows the updated geometry file with only the two inputted cross sections and interpolation of the remaining cross sections.
To complete a sediment analysis in HEC-RAS, quasi steady state hydraulic conditions are required. The input “flow series” matched the measured discharge values from the experiment and the downstream boundary condition was selected to “normal depth”. Normal depth requires the friction slope, which was assumed to be the designed channel slope. The quasi steady flow editor also requires temperature information, which was set to 20°C for the experiment duration. The fall velocity was selected as the Rubey method. Exner 5 for bed sorting and armouring method was used throughout.

The sediment input data is the final section necessary for transport analysis. Since the flume has an outlet weir at a known elevation, this value was chosen as the minimum elevation for erosion to occur at throughout the reach. The extent for bed development was selected just outside the initial bank extents, this allows for the use of the bank stability and toe erosion model (BSTEM). The bed gradation information was inputted with the Lafarge concrete sand values. Two transport functions were analyzed, the Meyer-Peter & Muller and Engelund & Hansen, as described in Chapter 2. The sorting method was set to Exner 5 and the fall velocity method was set to Rubey. The sediment boundary condition was chosen as a sediment load series at the upstream boundary. Since no sediment was fed to the channel during the experiments, the incoming sediment load was set to zero throughout the experimental runs. The gradation of the incoming sediment is required in the model even though no sediment is fed. It was set to 100% fines (100% passing 0.002 mm sieve).

Computation time was set to the same value of the time-steps in the laboratory experiments (10 minutes) and the model was run for the same duration as the design hydrographs. Model outputs included the cross sectional elevation changes, sediment transport, and bed armouring, amongst many other available output options.
Chapter 5: Results and Discussion

This chapter is organized in five sections including: sediment transport, bed morphology, planform morphology, comprehensive analysis, and the effect of unsteadiness. The first three sections will look at the development of the channel discretely, with respect to each section. The comprehensive analysis will then examine the inter-relationships between sediment transport, bed and planform morphological development. The final section of this chapter looks into the effect that the unsteady flow has on channel development.

5.1 Sediment Transport

This section will focus on the transportation rates of sediment through the channel. The movement of sand through the flume was quantified for each experiment with the use of a sediment catch at the outlet tank. The collection of sediment allows for analysis and comparison with the flow data, existing equations, and hydraulic model results. The single sediment catch at the outlet isn’t as extensive as previous set-ups have been (Curran et al., 2015), but provides sufficient data. An investigation into localized sediment transport rates won’t be included or explicitly analyzed in this section.

5.1.1 Laboratory Measurements

This subsection will focus on the results obtained from the physical measurements of the sediment transport and flow rate. The measured sediment weight at the output was averaged over each time-step to quantify a sediment transport rate for that period. Figure 10 highlights the measured sediment transport rates with time through the channel. The averaged flow rate for the whole experiment, or time-step in the case of EXP C, is also presented in Figure 10. Any minor flow variations were deemed negligible on the overall sediment transport for each time-step. The measured flow rate data for each minute of the experiments is found in Appendix A (Table 12, Table 15, and Table 18).
Figure 10: Temporal variation of sediment transport for experimental runs: a) EXP A; b) EXP B; c) EXP C
Figure 10 shows the variation of the sediment transport over the duration of the experiments. In general, the relationship between steady flow conditions and sediment discharge is one-to-one (Ahanger et al., 2008); The one-to-one ratio suggests that a single discharge will produce a single sediment transport rate. However, the results of EXP A and B do not show a consistent one-to-one ratio. The varying relationship is due to the initial development and sorting of the channel until an equilibrium condition is met. Figure 10 (a) and (b) show a larger amount of transport at the beginning time-steps before reducing somewhat exponentially towards the end. Equilibrium is met near 90 min in EXP B and 110 min in EXP A. At this point the sediment transport rates level out and show one-to-one correspondence with the steady discharge. The results of EXP A and B were similar to that obtained by previous researchers (Guney et al., 2013; Lajeunesse et al., 2010); they too, were completed without a sediment feed and saw an initial period of higher transport rates before decreasing through time. This initial period of higher rates can be attributed to the sorting of the bed and the development of the channel to reach equilibrium. The morphological response of the channel to the initial flow will be discussed further in Sections 5.2 and 5.3. Madej et al. (2009) did supply a sediment feed that was periodically turned off. The resulting periods without the sediment feed saw the peak sediment transport occurring immediately after the feed was turned off. The sediment output after the sediment feed was turned off also saw a sorting phase of varying transport rates before decreasing exponentially.

The relatively lower flow rate in EXP A resulted in a longer sorting period (approximately 40 min) before exponentially decreasing than the sorting period observed in EXP B (approximately 20 min). This decrease in sorting time as the flow rate increases is also clearly seen across the four experiments completed by Guney et al. (2013). This could be attributed to the higher flow rate causing larger particles to move and expose the smaller particles for transport. This phenomenon has been noted by others (L. Wang et al., 2015). This coincides with time to equilibrium findings from earlier, suggesting that greater flow intensities cause shorter sorting periods and a quicker time to sediment transport equilibrium.

Another study focused on steady flow rates with the impact of sediment feeding. The flow rate was held constant during the experiment, but the sediment feed had two different feed rates (Madej et al., 2009). After each aggradation phase (one high and one low feed rate) the sediment was turned off for a period of degradation. The sorting phase in the degradation period was longer following the higher sediment feed. The lower sediment feed rate produces less large, armouring particles on the bed, thus allowing a quicker sorting period once the feed is shut off.

Although the transport rates exponentially decrease, they eventually reach a steady, constant bed load transport rate. These constant bed load transport rates have previously been noted to occur in flume studies for up to 25 hours of continuous discharge (P. A. Nelson et al., 2015). However, the sediment
transport at the end of EXP A, B, and C were sufficient that any additional sediment transported would have a negligible effect on total sediment transport and morphological adjustment.

The results of EXP C, shown in Figure 10 (c), match similarly with EXP A and B in that a decrease in sediment transport is observed during the early stages of the run before the flow rate increases along with the sediment transport rates. Since the first time-step in EXP C was set to 30 min, the sorting and development phase effects on the average sediment discharge that occurred in EXP A and B with the 10 minute time-steps was not observed.

After the initial sorting period and low flow time-steps in EXP C, the sediment transport rates increase with increasing flow rate. This is seen in some of the transport equations (Bagnold, 1966; Meyer-Peter & Müller, 1948; Yalin, 1963) in that the fluid shear stress (Eq. 6) is dependent on the flow condition (Eq. 7) while the critical shear stress is reliant on only the bed parameters (Eq. 9). The maximum sediment transport rates occurs at the peak discharge rate. This is similar to the results seen by L. Wang et al. (2015) in that their peak sediment discharge occurs slightly after the peak flow. The peak flow in EXP C is broken into two time-steps, with the peak sediment discharge occurring after the first of these time-steps.

The total flow volumetric discharge (m³) under the hydrograph of EXP C (from time t = 30 min to t = 150 min) has the same total volumetric discharge of EXP B. Comparing the sediment discharge from the hydrograph in EXP C with the discharge from EXP B showed interesting results. The amount of sediment exiting the flume in EXP C was 120% of that exiting the flume during EXP B. This number would be even higher since EXP C excludes the sorting phase, which makes up the largest portion of sediment discharge in EXP B. This under representation of sediment yield during steady flow conditions has been noted in previous studies (Lee et al., 2004; L. Wang et al., 2015) when compared with unsteady flow. The under representation is attributed to the high sediment discharge during the rising limb of EXP C that the steady flow doesn’t produce. The sediment yield at the peak flows and the flows above the median make up the majority of the total yield. For EXP C, the sediment yield during the flows above the median (1.11 L/s) made up over 90% of the total sediment yield.

5.1.2 Hysteresis

Hysteresis is the delaying effect that occurs when forces, in this case shear forces from the action of the flow, acting on the bed change. Because of this retardation effect, sediment transport rates will vary for
the same flow rate on the rising and descending limbs of the hydrograph (Brownlie, 1981; Seeger et al., 2004). The cause of hysteresis has been studied previously on sand and gravel beds (Ahanger et al., 2008; Allen & Collinson, 1974; Beschta, 1987; Kuhnle, 1992; Reid et al., 1985; Ten Brinke et al., 1999). Noted causes of hysteresis in sand bed channels include bed forms, bed armouring, and lack of sediment supply.

Maximum sediment transport rates occurring on the rising limb corresponds with clockwise hysteresis, while larger yield on the falling limb produces a counter clockwise hysteresis. Other types of common classes of hysteresis loops were identified by Williams (1989). Ahanger et al. (2008) note that clockwise hysteresis of sediment transport rates is the most common type found in nature.

Similarly with other sediment starved experiments (De Sutter et al., 2001; L. Wang et al., 2015), the sediment transport rates in EXP C experience a clockwise hysteresis (Figure 11), with higher sediment transport rates occurring on the rising limb. The clockwise hysteresis is typically observed for systems with little to no sediment feed (Williams, 1989; Wood, 1977).

![Figure 11: Clockwise hysteresis occurring during EXP C](image)

Figure 11 clearly illustrates the clockwise hysteresis experienced in EXP C; the sediment transport rates increase on the rising limb as the flow rate also increases before falling at the beginning of the receding limb. On average, the sediment transport rate on the rising limb was 2.86 times greater than values obtained for the same flow rate on the falling limb. The large discrepancies of sediment transport rates at the low flow rates are attributed to sorting and developing phase of the channel. These low flow rate values were excluded when determining the average.
5.1.3 Fractional Sediment Transport

The analysis of the sediment transported out of the flume was analyzed using a fractional bed load mobility approach. This analysis was first proposed by Parker and Klingeman (1982) and has been applied in previous studies (L. Wang et al., 2015). The fractional bed load mobility examines the sediment distribution characteristics of sediment being removed and compares them to the original distribution of the sediment in the channel. The equation can be written as:

$$\psi_i = \frac{p_i}{F_i}$$

Equation 27

Where $\psi_i$ is the fractional bed load mobility number, $p_i$ is the fractional proportion (by mass) of a sediment class from the transport sample, and $F_i$ is the fractional proportion of the same sediment class in the original bed sample. It is seen that if $\psi_i = 1$ the grain size class being transported is equal to the original bed. If $\psi_i > 1$ then the sediment class being transported is over-represented meaning a higher fraction is being transported than what was originally in the bed, and if $\psi_i < 1$ then the transported sediment class is being under-represented meaning a lower fraction is being transported than what was originally in the bed. Reasons for over-representation could be attributed to grain protrusion and under representation could be attributed to grain hiding effects (L. Wang et al., 2015).

The sediment classifications used in the research are organized in four categories: gravel, coarse sand, medium sand, and fine sand. The gravel is assumed to all be “fine gravel”, that being retained on the No. 4 to No. 10 sieves. The coarse sand was the grain size class retained on the No. 10 to No. 20 sieves, medium sand was the No. 20 to No. 60 sieves, and fine sand was calculated as the material caught on the No. 60 to No. 200 sieves in addition to pan. The size range of the sediment classes is provided below in Table 9.

<table>
<thead>
<tr>
<th>Sediment Class</th>
<th>Size Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>2.00 – 4.76</td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>0.841 – 2.00</td>
</tr>
<tr>
<td>Medium Sand</td>
<td>0.250 – 0.841</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>0.074 – 0.250 (+ pan)</td>
</tr>
</tbody>
</table>
Analysis of the fractional bed load mobility was undertaken for all three experiments for their entire durations. The resulting data is shown below in Figure 12.

Figure 12: Fractional bed load mobility for different sediment characteristics: a) EXP A; b) EXP B; c) EXP C
The fractional bed load plots provide insight into the variation of the sediment transport rates through time. As expected, a general trend of fining of the bed load with time is observed; this is most clearly seen in Figure 12 (b). The fining of bed load material has been noted to occur in the natural environment because of bed armouring effects (Frings, 2008). These armouring effects were found in the present experiments and will be discussed further in Section 5.2.2. This armouring effect helps explain the fractional bed loads for the different sediment classes converging as the flow rate increases in EXP C.

The fining trend during EXP A and B for the steady flow events could be caused by the lack of a sediment feed (sediment starved). Without the introduction of sediment at the upstream end of the flume, once the bed has sufficiently armoured itself, the sediment transported reduces (Figure 10 a and b). The lack of sediment feed in natural rivers has been noted by Sheary (2017) to cause fining of the sediment transport after a dam was imposed on a natural channel. Guney et al. (2013) also observed higher sand transport per total load as time increased during their flume experiments. It would be expected that the sediment class mobility would level off at their respective fractional bed load mobility numbers once equilibrium is reached. This was somewhat observed in EXP A between 90 and 120 min and in EXP B between 60 and 90 min. It was also interesting to note that the fractional bed load mobility of the sediment classes was near the same value for the coarse and medium sands (0.8 and 1.3, respectively) at the equilibrium point for sediment transport rates in EXP A (110 min) and EXP B (90 min). The values for the other two sediment classes highlighted the fining in EXP B as the fractional bed load mobility numbers were higher for the fine sands and lower for the gravel class in EXP B.

The initial fractional bed load mobility numbers for each class are generally clumped together for the first few time-steps in all three experiments, meaning an equal proportion of sediment classes to the original bed structure is being transported; this can be attributed to the first flush of sediment to the flow before any armouring and bed forms develop. During these initial time-steps, since the shear stress exceeds the critical shear stress of each sediment class \( \tau^* > \tau_{cr-gravel}, \tau_{cr-coarse sand}, \text{etc.} \) the fractional bed load mobility numbers for each class are near 1. These results are in agreement with previous field measurements (Frings, 2008; Kuhnle, 1992; Lenzi et al., 1999) that found that all grains are equally mobile during fully mobilized transport conditions. Additionally, Frings (2008) found that unimodal sediment distributions caused severe hiding effects which in turn causes equal entrainment mobility across the distribution. The one exception to this in the experiments is the gravel class in EXP A. The gravel class in EXP A maintains a low fractional mobility number even at the beginning of the experiment. This could be attributed to the lack of bed form developments, causing a greater proportion of smaller particles to exit the flume.
The increase fractional bed load of the larger classes, and subsequent decreasing of smaller classes, during the final time-step in EXP A and C may be attributed to the small amount of material exiting the flume. Having reached equilibrium conditions, the resulting sediment transport is very small; as such the presence of any larger particles substantially increases its percent retained value. At the end of EXP C, the fine sands experienced a significant drop in fractional bed load mobility. This could be attributed to coarsening of the thalweg and the migration of the fine sediments to the point bars at the higher flow rates. The amount of fine sands available for transport (i.e., exposed on the channel bed surface) at the base flow rate could have already been flushed through the flume with the first low flow time-step (140-150 min). The abundance of fine sands available for transport during the final 30 min base flow time-step would be much lower and cause a higher percent mass of larger sediment classes to appear in the outflow distribution.

After the initial armouring at the low flow rates in EXP C, the increasing flow rate causes the larger particles to begin movement and transport again through the rising limb of the hydrograph, as seen in Figure 12 (c). The increased flow rate cause a higher fractional mobility of the larger sediment classes than the smaller two classes (time 60 to 90), but once the hydrograph enters its receding limb, the fractional bed load of the classes invert immediately. The increased coarseness of the thalweg for the large flow rates causes the fractional bed load mobility numbers for the sediment classes to divert significantly as the receding limb decreases. When comparing the fractional bed load mobility (Figure 12 c) against the hysteresis effect (Figure 11), not only does the rising limb produce more sediment transport, but it also produces a coarser fractional bed load transport rate. This is an important finding. As noted in previous studies (Ahanger et al., 2008; Williams, 1989), clockwise hysteresis is the most common class of hysteresis. Then the bed load transport in the rising limb of the most common class of sediment transport hysteresis produces a higher amount of coarse particles in movement. This would suggest, in nature, during spring when the flow rates are high (rising limb) due to snowmelt the sediment moving in those streams is larger, both in magnitude and size, than the sediment transported during the summer months (falling limb). This finding may help explain or assist in understanding other regimes outside of the hydraulic and hydrologic engineering field, such as the yearly ecologic cycle of a channel.

The effects of the fining of the sediment transport rates can also been seen in the plots of the $D_{50}$ of the sediment yield (Figure 13 and Figure 14). Figure 13 shows the $D_{50}$ of the transported sediment for EXP A and B, while Figure 14 shows the same for EXP C.
Much like the fractional bed load mobility figures, EXP B shows a clearer fining of the transported $D_{50}$ through time. During the initial high sediment transport rate during the sorting phase, the $D_{50}$ of the sediment yield was near or higher than the initial bed composition. This corresponds with the converging fractional bed load mobility (Figure 12 b). But once the fractional bed load classes diverge, the fining of the sediment yield is also observed in the variation in transported $D_{50}$ shown in Figure 13. An interesting observation is that the $D_{50}$ of the transported sediment in EXP A had a higher value at the end of the run compared to EXP B. This could be attributed to the lack of excessive fines in the exiting sediment during EXP A, possibly due to the hiding effects of the larger particles at the relatively lower discharge and the relatively smaller bed forms.
The $D_{50}$ of the transported sediment in EXP C varied similarly to the fractional bed load mobility. An initial decrease was followed quickly by a sharp increase as the flow rate increased before falling with the receding hydrograph limb (Figure 14). Most notable from this plot is that the peak $D_{50}$ value didn’t correspond with the peak flow as expected. The $D_{50}$ of the transported sediment plateaued on the rising limb near 0.93 mm, with the maximum $D_{50}$ occurring at time 60 min and 70 min. It was expected that the $D_{50}$ would continue to rise, reaching a maximum value at the peak sediment discharge at 90 min. However, previous studies in the literature suggest that the results in Figure 14 weren’t completely unexpected. L. Wang et al. (2015) also observed the peak $D_{50}$ of the transported sediment occur in the rising limb prior to peak flow and peak sediment transport. The maximum $D_{50}$ occurring prior to the peak discharge could be a result of the lower fractional presence of medium sand (see Figure 12 c, at 60-70 min) in the yield on the rising limb. The lower fractional presence of fine sands impacted $D_{50}$ of the transported sediment as opposed to the medium sands in a previous study (L. Wang et al., 2015). Madej et al. (2009) noted that the $D_{50}$ fluctuated around a single value during the degradation phases. The results of Madej et al. (2009) are similar to those seen in EXP C and in EXP A during the sorting phase. Further investigation to assess if the maximum $D_{50}$ is a function of the bed material or flow is required.

Examining the results of EXP C, coupled with a previous study (L. Wang et al., 2015), it appears that the maximum $D_{50}$ occurs on the rising limb of the hydrograph prior to the maximum sediment yield and is more a function of the bed material rather than the flow.

The gravel class seems to have had the largest effect on the $D_{50}$ plots. The times with an increase in fractional gravel bed load (Figure 12) correspond with an increase with the $D_{50}$ value (Figure 13 and Figure 14). The shapes of $D_{50}$ and the gravel fractional bed load mobility numbers are very similar across all three experiments. This is most clearly seen at the end of EXP A and C, where the $D_{50}$ increases in a similar fashion to the matching increase of the fractional gravel bed load. The large increase of the $D_{50}$ at the end of EXP C is exacerbated by the lack of fine sediment yielded in this time-step.

### 5.1.4 Comparison with Predictive Equations

The sediment transport equations (Eqs. 11, 13, 14, and 17) presented in Section 2.2 are evaluated and compared with the results of the three experimental runs (Figure 15). The importance of using an equation within its validity range, especially empirically derived formulas, ensures that predicted rates weren’t off by several orders of magnitude in value (Meng et al., 2016; Recking, 2010; Recking et al., 2012; Talukdar et al., 2012). The equations evaluated in Figure 15 are within the acceptable domain, but evaluation can
only occur at the initial time-step as there is no incoming sediment feed. This causes an issue with $D_{50}$ available for transport, which is used in all the sediment transport equations (Eqs. 10 and 17). Further investigation of a couple of the transport equations (Engelund & Hansen, 1967; Meyer-Peter & Müller, 1948) is completed using HEC-RAS, as it can update the $D_{50}$ of the bed through time.

![Figure 15: Comparison of measured bed load transport and predicted values from common bed load transport equations](image)

Figure 15 shows the measured sediment transport for two separate flow rates (0.8 L/s and 1.1 L/s) and the estimated values from various sediment transport equation. There were two separate measured values for the low flow (0.8 L/s) situation; one from EXP A and the other from EXP C. EXP C experienced greater sediment transport than EXP A. The higher sediment transport from EXP C is due to the occurrence of considerable erosion at the outside bank of the first meander, it is believed that the sediment transport from EXP C is an anomaly as this amount of erosion wasn’t noted in EXP B when the flow rate was higher (1.1 L/s versus 0.8 L/s). However, using the collected data, a few observations can be drawn. Most notably, three of the four equations over-predict the amount of sediment transport. These three equations
all employ the Einstein “phi” parameter (Eq. 10) and are using shear velocity as the parameter to determine transport capacity. The only equation that uses an explicit value of the flow parameters is the Engelund and Hansen equation (transport capacity by stream power), which performs well at the low flow rate.

The slope of the linear averaged Yalin equation and Bagnold equation were similar to that of the measured values in EXP B and C. Conversely, the linear averaged slope of the Meyer-Peter and Muller equation is similar to the measured values in EXP A and B. Since it’s believed the EXP A and B results were more realistic, the Meyer-Peter and Muller equation appears to provide the best fit in terms of trend. However, the Meyer-Peter and Muller equation over-estimates the sediment transport the most of all three equations. A possible reason for the over-prediction of sediment transport from the equations is due to the hiding effects of the larger particles in the flume, which was noted in previous studies investigating bed load transport equations versus field measurements (Recking et al., 2012). This over-prediction is a by-product of the flume not employing a sediment feed to the channel. The lack of sediment introduced to the flume (control volume) coupled with the sediment output show that equilibrium of the system is not obtained (what goes in does not come out). The equations utilizing the Einstein “phi” are based on an equaled control volume and sediment continuity. This would suggest that if sediment was supplied to the flume, the equations (Bagnold, Yalin, and Meyer-Peter & Muller) should perform more accurately.

Sediment supplied to the system not only provides a base value for movement it also promotes further sediment transport downstream as the particles collide with one another, dislodging sediment, decreasing hiding effects, and providing more sediment available for transport (Z. Y. Wang, 2015). This is observed in all three experiments with the sediment starved set up, where the outlet straight section of the laboratory channel observed much more erosion and movement than the inlet section due to the sediment particles being carried through.

The developments of the bed forms seem to have had the largest impact on the Engelund and Hansen equation. As it represents the measured values at the low flow when little bed development occurred (EXP A), it under-predicts the sediment transport for the higher flow rate. The trend line for the Engelund and Hansen equation is also much less than both the measured values. The impact of bed forms on the Engelund and Hansen equation will also be discussed in the following Section (5.1.5), where the equation performs better in the model at the tail of the experiment when little bed development is occurring. The bed development also has an effect on the local cross-sectional average velocity which is employed in the Engelund and Hansen equation. Pool areas would produce a lower flow velocity than riffle areas, causing a localized difference in sediment transport. The armouring of the bed helps explain the morphological response of the channel to these localized differences and the overall channel sediment yield with respect
to the Engelund and Hansen equation. An average velocity term is assumed across the cross-section of the channel as well as the length.

5.1.5 HEC-RAS Modelling Results

The use of HEC-RAS 5.0.3 with 1D flow and sediment transport analysis was completed for the runs in the experimental channel. The incremental computing time-step was set to 10 minutes and flow data input was the average time-step flow rate for the duration of the computing time. The outputs from HEC-RAS were extensive; however, the focus was on the sediment transport rates and the total sediment yield. Although the varying $D_{50}$ of the bed surface was an intriguing output, not enough quantifiable measured data currently exists to make a comparison. Figure 16 shows the computed sediment transport rates and cumulative transport for the measured values, Meyer-Peter & Muller HEC-RAS model results, and the Engelund & Hansen HEC-RAS model results across the three experimental runs.
Figure 16: Measured and modelled sediment transport rates through time and cumulative sediment yield: a) EXP A; b) EXP B; c) EXP C
Figure 16 (a) shows the results of HEC-RAS model for EXP A. Modelled sediment transport rates, both Meyer-Peter & Muller and Engelund & Hansen, match the physical measurements at various time-steps. The Meyer-Peter and Muller analysis performs better during the sorting phase (20 to 40 min) while the Engelund and Hansen analysis was closer to measured values at the end of the experiment (60 to 120 min). The largest discrepancy between the measured and modelled transport rates occurs at the initial time-step, where the model values were much lower than the measured rates. This is twofold in that the model can’t pick up the large sediment output due to channel adjustments and the time it takes for sediment to exit the flume with the flow. Since the channel is sediment starved, the only location of sediment supply is in the upstream end of the channel, which takes some time to move through the flume; in the HEC-RAS model this first wave of sediment isn’t completed in the first computational time-step and as such, appears in the second time-step. In the second time-step a steep increase in sediment transport is observed; in fact, the largest sediment yield for both HEC-RAS analyses occur at this time-step (20 min). After 20 min, the cumulative yield from the Engelund and Hansen analysis is fairly similar to the measured values, with a slight over-prediction. The cumulative yield from the Meyer-Peter and Muller analysis is less than half of the measured after the first 20 min of EXP A. After 20 min, a sharp drop off in sediment transport rates for the duration of the experiments is observed with the Engelund and Hansen analysis. Conversely, a more linear reduction in the sediment yield through the entire duration of the experiment is observed with the Meyer-Peter and Muller analysis. In this respect, the Engelund and Hansen equation is more adept at recognizing the “quick” sorting phase of the channel. At the end of EXP A, the two model results for cumulative sediment yield straddle the measured value, but the Engelund and Hansen method appears to provide a more reasonable approximation through time.

The model results of EXP B and C (Figure 16 b and c) didn’t perform as well as EXP A, but the models did provide some interesting insights. First, the Engelund and Hansen analysis for EXP B was very similar to EXP A in that a large sediment yield occurred at 20 min before decreasing to lower sediment transport rates. The Engelund and Hansen analysis also produced similar sediment transport rates to the measured values at the end of EXP B and C. Another interesting observation from the models regards the hysteresis observed during EXP C. The Meyer-Peter and Muller model predicts a clockwise hysteresis as measured in the lab, but the Engelund and Hansen model predicts a single-valued line hysteresis. The single-valued line hysteresis is one that produces the same values on both the rising and falling limb (Williams, 1989). Additionally, in EXP C, the peak sediment yield from the Engelund and Hansen method occurs within the first time-step (30 min). The reason this occurs after 30 min is due to reporting the results of the first three time-steps from the model into a single point. One final interesting observation in EXP C is that model predictions for sediment transport rates in the final two time-steps.
were identical in both the Meyer-Peter & Muller and Engelund & Hansen models; however, at the final two time-steps in EXP C these model values over-predict the measured values from the flume.

The resulting outputs from HEC-RAS were less accurate for EXP B and C; however, the model performed well for estimating the sediment transport rates and total yield for EXP A. In general the Engelund and Hansen method in HEC-RAS provided a better representation of measured values at the later time-steps after the sorting phase. The slope of the Engelund and Hansen cumulative transport line is very similar to the slope for the measured values. This holds true in EXP B and C where the slope of the line matches even though the location on the graph is substantially lower. This result demonstrates that the model is able to provide accurate results in the later time-steps after the sorting phase. HEC-RAS isn’t designed to analyze large sudden geomorphic changes such as the ones witnessed in the flume during the sorting phase.

The inability to model the large geomorphic channel adjustments and sediment transport rates is more clearly seen in EXP C, in which the two models fail to predict high sediment transport during the rising limb of the hydrograph. In fact, the Engelund and Hansen analysis predicted the largest sediment yield to occur in the first 30 min time-step. The Meyer-Peter and Muller analysis similarly under-predicted the sediment yield during the rising limb of the hydrograph, but it did predict an increased sediment transport rate with increased flow rate. This lack of sediment yield could be attributed to the models inability to accurately pick up the morphology, especially the bank erosion, as this provided much of the sediment supply in the flume.

Morphological adjustments were attempted with HEC-RAS, but the results were poor. Due to the one-dimensional sediment transport behaviour, bed development can only be modelled as uniform across the whole cross sectional width of the channel. Figure 17 shows an adjustment to the bed at Apex 2 at the end of EXP C using the Meyer-Peter and Muller transport method, with a minor deposition around 4 mm across the bed cross section. The resulting cross sections using the Engelund and Hansen transport method were indifferent from the initial cross sections. HEC-RAS did note the changing $D_{50}$ of the bed surface but couldn’t produce an accurate bed elevation adjustment as it doesn’t contain the appropriate morphological processes in its 1D version.
Although the BSTEM feature wasn’t used for the results shown in Figure 17, by allowing for bed development outside the initial bank limits, HEC-RAS can model some bank development. Slumping at the top of the channel occurred at the inside and outside banks, but larger slumping occurs at the outside bank as the new channel cross section couldn’t tie off in the boundary limits. In this aspect the model does recognize slumping of the banks and that the outside bank would incur more erosion than the inside, unfortunately, the results don’t accurately agree with the observed results. The reason for the model under-predicting the bank adjustment is most likely due to the sediment properties utilized in the model. The flume consisted of non-cohesive sand throughout, but the sediment options in the banks in HEC-RAS were limited to default sediment classes and parameters. The sand class was chosen but it assumes cohesiveness within the sediment. As such, the cohesiveness of the sand helps stabilize the bank from erosion, causing the modelled channel to appear more stable than flume. The ability to input a sediment class for the banks in HEC-RAS is possible, but some of the required information wasn’t available for the concrete sand (critical shear stress, erodibility, etc.).

Analysis of the flume experiments with HEC-RAS was an interesting endeavour that provided some valuable feedback. Unfortunately HEC-RAS can’t accurately analyze the large geomorphic changes to the channel at the beginning of the experiments, but the model provided accurate sediment transport rates at the later time-steps. Analyzing the data in EXP A or after the sorting phase in EXP B provides insight.
into the model accuracy. The Engelund and Hansen model performs better with respect to sediment transport rates at the latter time-steps. This is seen in the slope of the cumulative sediment yield line matching closely with the measured. The Engelund and Hansen model also picked up the “quick” sorting phase and produced a cumulative sediment plot more accurately through time, especially for EXP A. The bed development in the initial sorting phase grows in conjunction with 2D flow vectors through the bed forms, which can’t be accounted for in the 1D HEC-RAS model. This is also the reason greater emphasis is added to the results of EXP A, as it saw little geomorphic development. Comparable to Figure 15, the Meyer-Peter and Muller equation/model over-predicts sediment transport rates, while the Engelund and Hansen equation/model is closer at matching the measured sediment transport rates. In terms of issues with the HEC-RAS models, the lack of incoming sediment may pose similar concerns that have been brought up in previous studies (Miller et al., 2015), regarding model sensitivity to sediment supply. Miller et al. (2015) completed sediment modelling for a proposed bypass channel on the Yellowstone River at Intake Dam using HEC-RAS and completed a sensitivity analysis on multiple parameters, finding that the incoming sediment gradation was highly sensitive.

5.1.6 Summary

The sediment transport rates from the experimental runs were similar in that each had an initial sorting phase of high sediment yield before exponentially decreasing. This exponential decrease was expected since there was no sediment feed into the flume. The absolute equilibrium of the channel would occur when no sediment exits the flume. The sorting phase in EXP A was longer than that in EXP B, this was noted to be caused by the low flow being unable to move larger particles and access the smaller particles for transport. The longer sorting phase for lower flow rates has also been noted by previous researchers (Guney et al., 2013; L. Wang et al., 2015).

In the case of EXP C, a quasi-unsteady hydrograph was fed through the flume to investigate the impacts of unsteady flow on the channel. The channel produced a clockwise hysteresis of sediment transport, with higher sediment transport occurring on the rising limb of the hydrograph (Figure 11). Williams (1989) noted that clockwise hysteresis is the most common type of sediment transport flow rate hysteresis in the natural world and other sediment starved flume studies also often witness clockwise hysteresis (De Sutter et al., 2001; L. Wang et al., 2015).

The analysis of the sediment distribution exiting the flume through time in the experiments demonstrated a general fining trend. The proportion of smaller sediment classes, notably fine and medium sand, in the
sediment yield generally increased as the experiment progressed. The fractional bed load mobility method (Eq. 27), developed by Parker and Klingeman (1982), was utilized to analyze the fining trend. In EXP C it was quantified that during the rising limb of the hydrograph, the fractional bed load mobility of the larger particles was higher than the falling limb. This suggests that coarser sediment is transported in conjunction with the higher transport rates on the hydrograph rising limb. This finding may assist with a better understanding of other natural phenomenon in other research fields outside of hydraulics. The $D_{50}$ of the sediment yield also demonstrates the fining through time. The $D_{50}$ of the sediment transported in EXP B clearly shows the fining trend (Figure 13). The $D_{50}$ of the sediment output was near the initial $D_{50}$ of the bed at the beginning of the run before decreasing. In EXP C, when the flow rate increased so too did the $D_{50}$ of the sediment yield, reaching a maximum prior to peak sediment transport rates. This observation was also noted in previous research (L. Wang et al., 2015).

Some sediment transport equations (Bagnold, Yalin, Meyer-Peter & Muller, and Engelund & Hansen) were compared against the measured sediment transport from the flume. In addition, two HEC-RAS models were run, one implementing the Meyer-Peter & Muller transport equation, the other using the Engelund & Hansen equation. In general, the equations using shear velocity as an indicator for sediment transport over-predicted the sediment yield. The Engelund and Hansen equation utilizes stream power as its indicator for sediment transport and produced more accurate results with the measured values. However, bed forms in the channel seemed to have had the largest impact on the Engelund and Hansen equation. Similar to the analysis of the existing sediment transport equations, the sediment transport rates were higher with the Meyer-Peter and Muller (shear velocity equation) HEC-RAS model than the measured flume values. This was true at the end of the experiments after the sorting phase, which HEC-RAS couldn’t pick up. The inability for HEC-RAS to model large and sudden sediment yields associated with geomorphic changes to the channel could be caused by the inability of the 1D model to match the 2D flow vectors associated with the developing bed forms. This was clearly seen in EXP C (Figure 16 c) where the model results were much lower than the measured. However, the HEC-RAS models did provide valuable feedback; especially in EXP A, where the Engelund & Hansen method performed better through time and produced accurate results, principally at the latter time-steps closer to equilibrium. The other interesting output from the HEC-RAS models was that the Meyer-Peter & Muller model produced a clockwise sediment hysteresis while the Engelund & Hansen model produced a single-valued line hysteresis.
5.2 Bed Morphology

This section will focus on the development of the bed through time, including the bed forms, bed gradations, and the location of the bed forms. The DEMs of the flume developed using Agisoft PhotoScan provide the ability to analyze the geomorphic changes to the bed through time. The bed forms can be analyzed anywhere in the channel; however, at this time the only location with quantifiable bed gradation data occurs at the apex of the second meander. This is because the only bed sample taken at the end of the experiments came from the apex of the second meander; the sample was taken across the whole cross-section (bank to bank). As such, more focus will be provided on this region of the channel throughout the whole section.

5.2.1 Bed Formations

With the 3D DEMs produced from PhotoScan, analysis of the bed formations was undertaken. As noted in Section 4.4, the use of six control points around the flume allow for model alignment and elevation control for each set of photos and the subsequent models created in Agisoft PhotoScan. Figure 8 shows a PhotoScan DEM file, where bed development and formations at the end of EXP B are shown. A comprehensive analysis of the entire bed development of the channel through time for each experimental run is seen in Appendix C (Figure 45 for EXP A, Figure 46 for EXP B, and Figure 47 and Figure 48 for EXP C) and Appendix D (Figure 49 to Figure 56 for EXP A, Figure 57 to Figure 64 for EXP B, and Figure 65 to Figure 78 for EXP C). The tables in Appendix C show the absolute elevation of the channel, while the tables in Appendix D show the difference in elevation from each time-step measurement to the initial bed elevations (termed hereafter, development plots). These figures present a general depiction of bed forms in the channel, including point bars, pools, and riffle structures.

Cross-sectional analysis of bed development is possible anywhere within the flume; however, the largest development was generally observed at the apexes. Apex 2 (refer to Figure 6) was chosen as the focal point for bed development analysis, as it is the least impacted by the effects of the channel inlet and outlet. Figure 18 shows the channel evolution at Apex 2 through time for each experimental run. The y-axis in Figure 18 shows the absolute elevation of the bed and the x-axis is shown with the dimensionless η value (Eq. 24). A negative η corresponds to the inside bank region and a positive η is corresponds to the outer bank region. Only a selection of time-steps are displayed in Figure 18. Complete plots for each apex in all three experimental runs is seen in Appendix E (Figure 79 through Figure 87).
Figure 18: Measured bed morphology at apex 2 through time: a) EXP A; b) EXP B; c) EXP C
The bed evolution of apex 2 (Figure 18) shows the impact the varying flow rates had on the bed morphological development. In general, the largest morphological changes occur within the first few time-steps. Some further adjustment in subsequent time-steps are observed, but this is due to the changing flow rates within the experimental run. Very little bed development was observed during the entirety of EXP A. Aside from the banks slumping in during the initial time-steps, no other substantial morphological adjustments occurred. Figure 45 in Appendix C shows that the little bed development at apex 2 is consistent with the other apexes in the channel in EXP A. EXP B on the other hand has notable bed developments. The presence of a point bar and a pool is quite noticeable after the first time-step. As noted before, the majority of the development occurs early (within the first 20 min). The rapid development of the bed with little adjustment later in the steady state experimental runs (EXP A and B) is in agreement with field observations (Church & Ferguson, 2015; Leopold & Langbein, 1962; Simons & Richardson, 1966). Similarly, these field observations also support the results of EXP C in that the rapid bed adjustments occur quickly with the changing flow rates. These rapid adjustments were more easily seen on the rising limb of the hydrograph for EXP C.

The point bar and pool at apex 2 in EXP B reach 90% of their final development size within the first 20 min and were at 99% of their final development size by 40 min. The development of the pool reaches equilibrium quicker than the point bar. This is possibly in relation to the fining of the sediment yield in that the armouring of the thalweg and pool didn’t witness more erosion while the fines moving downstream still had the ability to settle on the downstream point bars. Another possibility is that the idealized bed load transport path, shown in Figure 25, crosses the point bar without going through the pool section at the outer bank of the apex. As expected the point bar grows in mass and height, but some settlement after the initial flow discharge is observed in the pool at apex 2 in EXP B. This could be attributed to a few larger particles depositing in the pool to increase the bed armouring. This small accumulation of sediment in the pool also causes the transition point between pool and point bar to move (point of cross over with the initial bed, shown in Figure 19). The transition point is initially closer to the inner bank before moving outwards. The movement of the transition point outwards may be a possible explanation for the development of a second “step” in the point bar towards the end of EXP B.
The transition point in the channel is clearly observed to move outwards, as shown in Figure 19; Figure 19 is a zoomed in view of Figure 18 (b) showing the point of cross over with the initial channel bed moving through time.

Figure 46 in Appendix C shows the outward growth and downstream development of the point bar at apex 2 with time. Once again, this growth profile follows the idealised bed load transport path (Figure 25) along the outer edge of the point bar moving downstream.

EXP C also saw large development once the initial channel was exposed to the flow (during the first time-step), similar to the first two experimental runs. However, additional substantial deformation of the bed occurred as the flow rate increased. This is seen in Figure 18 (c) where large increases in the point bar height occurred from 50 to 90 min on the rising limb of the hydrograph. The largest development still occurs at the initial time-steps, but other significant deposits occur at 80 and 100 min. The point bar saw continual growth, while the pool section saw some initial growth with the increasing flow rate, reaching a maximum depth at 80 min, before beginning to accumulate sediment at the maximum flow rate (100 min). The subsequent falling limb of the hydrograph caused further deposition of material in the pool section. The deposition of sediment within the pool section between 80 and 100 min could be a response of the channel to the increasing flow rate by depositing large armouring sediment along the inner thalweg.
The supply for these larger sediments could be coming from the outer bank, as a second considerable slumping event occurred at the outer bank between 80 and 100 min. As the material from the outer bank slumps, the larger sediments were deposited in the pool region and thalweg to protect the bed while the fines from the bank transport further downstream to assist in point bar growth at the next apex or were a part of the increased sediment yield. The subsequent sediment deposition along the falling limb of the hydrograph is likely due to the growth of the lower point bar, as the lower flows can’t reach the top of the primary point bar. Of more interest is the deposition throughout the pool (120 min plot over the 100 min plot; refer to Figure 18 c) section at apex 2, especially at the outer bank. This large deposition could be due to bank erosion upstream of apex 2 depositing in the pool. Sand beds in rivers are quite responsive to discharge (Trenhaile, 2013) and previous field research has observed deposition of sediment as the water level fell (Neill, 1965); this may also explain the deposition of sediment in the pool section of apex 2 during the falling limb of the hydrograph.

Similar to EXP B, the transition point is observed to migrate towards the outer banks, across the channel cross-section through time in EXP C. The first few time-steps result in general point bar growth in height and width. This continues as the flow rate increases and the sediment classes available for bed load transport increases. Once the peak flow rate occurs (100 min) the slumping of the outer banks causes the transition point to move outwards significantly. At this point, the transition point crosses the channel centerline, meaning more than half the channel width is a point bar. Similar to EXP B, the growth of the point bar outwards may be the possible explanation for the development of the “step” in the point bar. With the maximum height of the point bar confined by the flow depth, as the point bar moves outwards at a quicker rate than the transition point, the stability of the sediment in the main point bar fails causing the “step” and subsequent growth of the lower point bar. The point bar slope reaches a maximum steepness near 25 degrees, in both EXP B and C, before the development of the “step” and lower point bar. Previous research has investigated the point bar depositions and their morphology in relation to the angle of inclination of the bank, finding that the bars become unstable as the slope reaches the angle of repose for the bed material (Kawai & Julien, 1996). This would suggest that for the concrete sand used in the present research, the angle of repose of the sediment would be near 25 degrees.

Point bars grew to near surface level during EXP C, showing that a large width to depth ratio was maintained and were similar to those seen in the field (Simons & Richardson, 1966). The point bars were near surface level during the peak flow rates of EXP C and even became exposed during the falling limb of the hydrograph.

A unique observation near the end of EXP C was the development of a braided section. At this point of the experiment, the flow rate on the hydrograph was low enough that the point bar had been exposed
above the water surface. The relatively lower flow rate was able to penetrate and erode the fines in the tail of the point bar at apex 2. After approximately 5 minutes, the secondary flow path had created a small secondary channel that slowly grew in width before the end of the final time-step. Additional information regarding this occurrence is found in Section 5.3 and Figure 36.

The development of the bed is useful in better understanding the development time of the channel. Unfortunately, little bed form developments were noted in EXP A and EXP C had varying flow rates so it was difficult to quantify their impacts on the development rate. EXP B on the other hand contained considerable bed form development and was completed under steady flow conditions. Figure 20 displays the development rate of the point bars in EXP B; the graph shows all three apexes in the channel.

As shown in Figure 20, the deposition rates for the three apexes in EXP B predominantly follow an exponential decay trend. The second meander, also shown in Figure 18 (b), is the only meander not to witness a strong exponential decay. Larger development at 20 min and 30 min is observed at apex 2 compared to the other two apexes. However, in general, all three apexes had a development time near 40 minutes. The highest deposition at the first time-step occurs at the first apex, which is expected, but the second largest deposition occurring at the third and final apex was a bit surprising. It was expected that
the first apex would reach equilibrium then the second and finally the third. Yet it appears that the all three apexes take a different route before reaching near zero values at 40 min. Subsequent time-steps show little additional development for the first two apexes, but the third apex observed a few time-steps with about a 1 mm vertical growth on the point bar. These 1 mm vertical growths only equate to about 5% of the total deposition depth, meaning the majority (85%) of the development occurs by 40 min. From a closer examination of the deposition numbers, it is observed that apex 1 has the majority of its deposition occurring within the first 20 min and apex 2 is predominately developed at 30 min.

An average of the three apexes was created to gain a better understanding of the development process in the entire channel. The average data points were fitted with an exponential line over the first 40 min (shown as the dotted line in Figure 20). The exponential response of development shown in this laboratory experiment supplements the findings of previous researchers (Church & Ferguson, 2015; Leopold & Langbein, 1962; Simons & Richardson, 1966) that the stabilization of a channel in the field occurs in a short time.

5.2.2 Bed Gradation

The bed not only adjusts in terms of bed forms, but the grain size distribution of the surface material also changes. Point bars were predominately made up of fine materials depositing along the inner bank, while the outer thalwegs contain coarser sediments (Kawai & Julien, 1996). Sediment samples were taken at the end of all three experimental runs at apex 2. These samples were taken from the active layer of sediment (approximately 1 cm below the pool) all the way across the channel, from bank to bank. The definition of the active layer depth was proposed as two times the $D_{90}$ of the sediment (Wilcock et al., 1996) and other definitions are discussed in Church & Haschenburger (2017), but the 1 cm depth used in the present research surpasses most of the recommendations. Figure 21 shows the gradation of the bed at apex 2 prior to each experimental run and at the end of each experiment. No intermediate samples were obtained as the collection process would disturb the in place bed forms causing interference with the channel development.
Figure 21: Bed gradation at apex 2 prior to experimental runs and at the end of each experiment

The initial bed gradation doesn’t change a considerable amount after each experimental run. The bed gradation at the end of EXP A is almost identical to the initial condition, while some differences were observed in EXP B and C. In the case of EXP A, where little development was noted, the slumping banks had the same gradation as the bed so any incoming sediment had the same properties. As such, the final bed surface remains very similar aside from lower quantities of fine sand compared to the original sample. This reaffirms the fining trend noted earlier, that only the smallest of particles were moved during EXP A. The larger sediment classes on the bed surface remained relatively unchanged throughout EXP A.

Moderate changes to the bed gradation after channel development were observed in EXP B and C. This is due to the samples being taken across the entire cross-section at apex 2. Bed forms were observed in both these experiments, but the increase in fines at the point bar were offset by the coarsening of the stream bed through the thalweg and pool section. A closer look at the fine point bars and coarse thalweg is seen in Figure 22. EXP B and C had similar gradations through the medium and fine sand classes. This shows that the point bars grow in similar proportion, as the percent sand by mass remains the same across the channel regardless of the two varying flow conditions. Although it appears that less coarse sands and gravels were present at the end of EXP B and C, the mass of coarser sediment is offset by the large mass of fines in the point bar. The primary difference between the surface gradation of EXP B and C is the
coarse sands; EXP B has a larger percentage of coarse sands (0.85 mm to 2 mm) than EXP C. This difference in a single sediment size may be reflective in the different discharges between EXP B and C. The maximum flow rates reached in EXP C were 130% of the maximum flow rates reached in EXP B, which may have been just enough to cause a “flush” of the 0.85 mm sediment class through the thalweg. Additional information on the bed gradation adjustment for EXP B is seen in Figure 23.

The blue and red ellipsoids in Figure 22 distinguish the point bar and thalweg sections at the apex. The light tan lines were shown to delineate the banks of the channel. This figure shows the channel at the end of EXP B. The deposition of the point bar is built-up from the initial elevation and consists entirely of fines, much like the ones seen on the surface.

Figure 18 (b) demonstrates the cross sectional impact of the point bar on total sediment gradation; every particle in the point bar, $-0.5 < \eta < -0.2$ and between 0 min and 120 min, is similar to those seen in the blue ellipsoid (Figure 22). With such a large volume of deposited sand in the point bar, the matching gradations in Figure 21 becomes more staggering. To offset the large presence of fines in the point bar, the thalweg becomes much coarser, with minimal small sediments present in the red ellipsoid boundary in Figure 22. The lack of fines is noticeable across the entire pool section but especially along the inner edge of the thalweg, while the outer bed and bank were more reminiscent of the initial bed condition. The total gradation curve for EXP B (Figure 21) is slightly finer than the initial bed sample, which is also shown as a percent retained bar graph in Figure 23.
The bars at the end of the experiment were lower than the bars at the start of the experiment for the gravel and coarse sand classes, they were near equal at the medium sand class (0.425 mm), and the bars at the end of the experiment were greater than the bars at the start of the experiment for the fine sand classes (Figure 23). The largest difference between initial and final conditions occurs with the 2 mm, 0.85 mm, and 0.106 mm classes. These three sediment sizes correspond to the gravel, coarse sand, and fine sand classes, respectively. This shows the importance of medium class sediment in the stabilization process, similar to previous research (L. Wang et al., 2015). The 0.425 mm sediment is near the initial condition for all three experiments (Figure 21). The medium sand class (0.425 mm) may remain similar to initial condition as it’s probable that the presence of this class is in both the point bar and the pool sections. For the flume, sediment, and channel design it appears that the 0.425 mm sediment is the most “important” sediment size during the equilibrium process. This is important for future stabilization and rehabilitation works in the real world, as the presence of the “important” sediment size (dependant on the location, sediment, and channel dimensions of the natural reach) must not be overlooked. Placing only large rip rap sediment doesn’t provide enough shielding ability to protect the smaller sediment from the flow. The medium class helps prevent the dispersion of the sediment classes across the channel from being much greater.

Figure 23: Bed surface gradation, shown as percent retained, in EXP B
The initial condition (Figure 21 and Figure 23) has a fairly uniform distribution across the channel bed, but after the bed development the distribution becomes much less uniform. Figure 22 shows this variability, but the location of the sediment classes were confined to the bed forms; fines in the point bar and coarser sediment in the thalweg. Any distribution anomalies in the initial condition were quickly sorted by the flow and distributed into the bed forms.

The armour ratio is the surface median grain size compared to subsurface median grain size (Guney et al., 2013). For the present experimental runs, the subsurface median grain size is the same as the original bed gradation. The armour ratio can then be calculated as the ratio of the $D_{50}$ of the surface sediment to that of the original bed. The armour ratio explains how the channel bed adjusts to the varying flow, such as coarsening the bed surface as flow rates increase. As a comparison for the armour ratio, the dimensionless total bed load will be used, which is the same as previous research (Guney et al., 2013). The dimensionless total bed load can be defined by the equation below.

$$ W_t' = \frac{W_t}{\rho_s B D_{50}^2} $$

*Equation 28*

Where $W_t'$ is the dimensionless total bed load, $W_t$ is the total bed load yield, and $\rho_s$ is the density of the sediment. Eq. 28 was first proposed by Bombar et al. (2011). The total bed load yield is the cumulative mass of sediment that exits the flume throughout the entire duration of the experiment.

Figure 24 presents the relationship between the armour ratio and the dimensionless total bed load. The three data points correspond to the three experimental runs.
A linear trend in armour ratio with the dimensionless total bed load is observed in Figure 24. This trend is similar to the findings of previous research (Guney et al., 2013). The correlation coefficient is near unity in both cases, 0.98 for the research in this thesis and 0.99 for the research completed by Guney et al. (2013). The three data points in Figure 24 correlate to EXP A (armour ratio equal to 1), EXP B (armour ratio equal to 0.88), and EXP C (armour ratio equal to 0.85). The armour ratios were all less than or equal to one as an overall fining of the bed occurred across the entire cross-section. The experimental runs with the largest sediment yield also produced the largest bed forms, which increases the overall fining of the channel cross section at apex 2. EXP A had the least amount of bed forms, as the bed gradation rarely changed and the sediment yield was very small. The sediment yield was very similar in EXP B and C (Figure 16) and so too was the bed gradation at the end of each run (Figure 21).

The results from the previous research (Guney et al., 2013) had the armour ratio data points across the entire cross-section greater than or equal to one, likely due to the straight confined flume restricting bed forms, notably point bars, throughout the channel. This promotes an armouring effect, similar to the red ellipsoid in Figure 22, throughout the entire flume.

Unfortunately, the two data sets (Guney et al., 2013; and the present research) fail match up with each other. Combining the two data sets still shows a linear trend, but has a much lower correlation coefficient; the coefficient decreases from near unity for the individual plots to a value of 0.51, suggesting a weak linear trend. The weak relationship is seen when examining the dimensionless total bed load at the higher values of the dimensionless total bed load. At these high values, the armour ratio is around 0.85 for the present experimental runs, but Guney et al. (2013) found an armour ratio near 1 for the same
dimensionless total bed load value. The reason for the differing results could be attributed to the uniqueness of each experimental set-up, as the flume and channel dimensions, sediment gradations, flow conditions, and channel sinuosity differ substantially between the two experimental set-ups. This can also be seen in the linear trend line of each research; the slope of the trend line in Figure 24 is much steeper (-4752) than the trend line from Guney et al. (2013) (-2577). The steepness of the trend line in Figure 24 is due to the slight fining across the whole bed, as opposed to the previous research (Guney et al., 2013) having a straight confined channel with more uniform bed forms. The samples taken at apex 2 had a severe variance in sediment class across the cross-section (Figure 22), but a general fining trend as a whole (Figure 23). This causes the overall fining to have had a large impact on the slope of the trend line.

The only location applicable for analyzing the armour ratio in this thesis’ research was at apex 2. Further bed gradations would be required to see the impact of the armour ratio at different locations in the channel and a holistic view of the armour ratio through the whole sinuous channel would be valuable. This holistic analysis is currently unattainable due to the lack of physical bed measurements, but in the future with the possible implementation of automated image based grain sizing (Adams, 2013), the analysis could be completed. It would be expected that the armour ratio would increase as more of the channel is included, due to the majority of the fines being located in the point bars at the apex. This would shift the data points more in line with the findings from Guney et al. (2013).

5.2.3 Pool Riffle Structure

Analysis of the bed up to this point has focused on the bed forms and sediment gradations primarily at the apex of the channels. Further examination to the impact of the bed at the apex sections from the upstream channel and downstream channel is required. An idealized geomorphic channel schematic is shown in Figure 25, describing the pool riffle structure of a sinuous channel along with the position of the point bars. These structures were also present in the channel in EXP B and C. The flow in the flume goes from right to left.

The alternate bar sequence (Figure 25) from Trush et al. (2000) presents the ideal geomorphic and particle locations. The observed bed forms in EXP B and C and the particle size on the bed correspond very closely with the idealized plot.
The flow in the present research is more reminiscent of the dark blue low flow channel in Figure 25. As such, the point bar protrudes further into the channel quickly developing into the pool structure. The sinuosity of the experimental channel is greater than the stream in Figure 25, this causes an elongation of the riffle zone between the point bars as seen in Figure 29. The particle sorting is very similar in the flume, with fine sands in the point bars and gravel sediment in the pool at the apex sections.

Figure 26 and Figure 27 show the absolute topography and development plot for EXP B and C, respectively. Figure 26 shows the channel at the end of EXP B (120 min) and Figure 27 shows the channel after the peak of the hydrograph in EXP C (100 min). The development plots present the difference in elevation in the channel from the absolute topography to the initial elevation of the channel prior to the start of the experiment. Development plots for EXP B and C through the experimental time-steps is found in Appendix D (Figure 57 to Figure 64 for EXP B and Figure 65 to Figure 78 for EXP C).
Figure 26: Planform topographic view of the channel at the end of EXP B (120 min) (flow from right to left): a) Absolute elevation; b) Development plot
Figure 26 (a) clearly shows the location of the point bars and pools situated around the apexes. The riffle section after the pool structure is a little more difficult to delineate, but the contour lines reveal the shallow area between the apexes. This plot also shows that the point bars remain centered at the apex (apex 1), but the later pool structures are situated further downstream of the apex (apex 2 and 3). The pool at apex 1 is situated upstream of the apex, the pool at apex 2 is centered at the apex, and the pool at apex 3 is situated downstream of the apex. When compared with the idealized structure (Figure 25), the bed topography at apex 3 matches up the best. This makes sense since the first apex, and to a lesser extent the second apex, is impacted by the sudden change from a straight channel (initial run up section) to a
sinuous channel. The riffle structure is almost identical after all three apexes with few contours between the pool structures. The riffle structure can also be distinguished from the development of the thalweg (Figure 34), which remains fixed between the developing pool structures. The backwater effects shown in Figure 25 were also clearly seen with the contours in Figure 26. The local area of slow flow at the downstream end of the point bar causes recirculation of water in the form of an eddy (Blanckaert, 2011; Kasvi et al., 2013); this local area experiences the backwater effects or backwater eddy. At the inner bank of the downstream end of each point bar the presence of the backwater eddies cause the erosion of the point bar and an area with greater flow depth. The backwater effects continue through time moving with the growth of the point bar. Figure 46 in Appendix C shows the DEMs through time for EXP B, where the backwater effect is present in the point bars from the first time-step (10 min) through to the end of the final time-step (120 min). The backwater eddy is initially near the apex of the meander bend after 10 min but moves downstream through time.

Figure 27 (a) shows the absolute topographical map just after the peak flow in EXP C. Figure 27 also clearly shows the locations of the point bars, pool structures, and the backwater eddies. The riffles were more difficult to delineate than those observed in EXP B, but the contours still reveal the presence of riffles. Figure 47 and Figure 48 in Appendix C shows the DEMs through time for EXP C, where growth of the point bars, pools, and backwater eddies were distinguishable. Figure 47, Figure 48 and Figure 35 also illustrate the stability of the riffle section with little changes observed in the contours and the thalweg remaining in a consistent position through time. The notable differences between EXP B and C is that the pool structure locations aren’t the same. The pool at apex 1 is somewhat downstream of the apex, the pool at apex 2 is upstream of the apex, and the pool at apex 3 is centered around the apex. The varying locations of these pools could be caused by the large geomorphic changes to the banks. As the outer bank (Figure 32 c) moves laterally causing the thalweg migration (Figure 35) at apex 1, it also impacts the location of the subsequent bed forms downstream.

The development plot of EXP B, shown in Figure 26 (b), at the end of the experiment differs from the absolute plot. The subtraction from the original bed elevation allows for the analysis of growth and normalization of growth along the entire channel length. The same amount of maximum deposition in the point bar (1.5 cm) and erosion depth in the pools (0.5 cm) was observed at all three apexes. However, the shape and area across all three apexes differ. The majority of bed development occurs at the first apex, subsiding in the downstream direction. The locations of the point bars and pools remained unchanged between the two plots. It appears that the pool location at apex 3 differs between the two plots, but the scale of the contour lines differ slightly. The “0” contour line at apex 3 in Figure 26 (b) matches up with the pool contour line at apex 3 in Figure 26 (a). The development plot also reveals the riffle area where
little change in elevation throughout the experimental run occurs. Similarly, Figure 27 (b) shows the development of the channel in EXP C, with the most notable difference (between Figure 26 b) being the large amount of erosion (blue areas) at the outer banks around the apex.

A delineated enlargement of apexes 1 and 2 from Figure 27 (a) is shown in Figure 28. The markings in Figure 28 outline the pool structures, riffles, and the locations of the backwater effects on the point bars. The subsequent photos, Figure 29 and Figure 30, show apex 1 and 2, respectively.

![Figure 28: Enlarged view of EXP C channel (focused on apex 1 and 2) at 100 min, highlighting the pool structures, riffles zones, and backwater eddies (flow from right to left)](image)

The delineation of the bed forms is aided by the contours in Figure 28; the contours outline the location of the pools and the areas experiencing backwater effects, while the riffles cross the contour lines near the cross-over/inflection point of the channel. This figure reveals the impact of the bank morphology on the bed forms. The considerable movement of the banks at apex 1 causes a greater degree of growth in the point bar at apex 1 and a more distinguishable backwater eddy at this location. The width of the pool structure remains constant across both apex 1 and 2, but the location in plan differs. Due to the outside
lateral bank migration at apex 1, the pool structure at apex 2 begins well before the apex and ends just after the apex. The riffle structures remain near the channel inflection point and this causes a unique buffer zone between the pool structure and the riffles. The inflection point location differs for the two riffle sections due to the bank migration at apex 1 being “higher” (larger y-axis migration) than apex 3 meaning the inflection point after apex 1 is “higher” in Figure 28.

Figure 29: Photograph of EXP C at 100 min focused on apex 1 (flow from right to left)

Figure 29 is marked up similar to Figure 28 to show the location of the bed forms at apex 1. From this perspective, the photo is able to display the outer bank region of apex 1 and the pool structure. The material on the bed at the apex is qualitatively larger than the other material in the channel. The point bar at apex 1 is distinguishable due to the large amount of fines and the backwater effects at the point bar reveal the presence of the larger materials, as outlined in idealized particle sorting figure shown in Figure 25. The riffle structure consists of a mixed blend of sediment classes. The sediment in the riffle zone is finer than the pool section but coarser than the point bar. The material in the backwater eddy appears to be somewhat similar and even larger than the material in the riffle structure, but this follows the particle sorting structure shown in Figure 25. The backwater eddy has material around the same sediment class as the riffle structure, especially at the beginning of the riffles. This is seen in Figure 29 with the material in
the green circle similar to the material between the pool structure (top blue ellipsoid) and the pink riffle arrows.

Figure 30: Photograph of EXP C at 100 min focused on apex 2 (flow from right to left)

Figure 30 presents an enlarged view of apex 2 at 100 min. The perspective provides a clear image of the inner bank and the point bar. The distribution of sediment across the point bar follows the particle sorting pattern illustrated in Figure 25, with the finest of materials being deposited along the inner most section and gradually coarse material deposited as the bar moves outwards. Similar to apex 1, the backwater effects are clearly seen at the downstream end of the point bar. The view in Figure 30 provides a clear view of the sediment gradations in the varying bed forms. The pool contains the coarsest sediment, followed by the riffle area, and finally the point bar. The location of the sediment classes in the pool section of Figure 30 differ from the idealized plot (Figure 25). The largest particles appear to be situated at the inner bank and bottom of the pool as opposed to the bottom and outer bank as outlined in Figure 25. This could be due to the angle of the photograph, as Figure 29 appears to have had the larger material along the outer bank from the opposite angle.
5.3 Planform Morphology

This section focuses on the planform morphological changes observed in the channel in each experiment. Planform adjustments occur for the changing flow regime in the natural world (Marren et al., 2014). The most visible planform morphology observed is the movement of the banks through time. As water flows in a river it slowly causes the erosion of the banks. In the event of a large flood, the river banks may completely shift and migrate large distances in a relatively short period of time. An example of the magnitude of migration of the banks of a river is seen in Figure 31, which depicts the movement of the Mackinaw River between 1951 and 1988.

![Figure 31: Historical aerial photos of the Mackinaw River from 1951 and 1988; flow is from right to left (Motta et al., 2012a, p. 22)](image)

The sinuous reach of the Mackinaw River creates a completely new morphological pattern over the 37 year time span. In addition to the movement and morphology of the banks, other planform adjustments were also occurring. The thalweg also changes with the migrating river.
5.3.1 Bank Morphology

The banks of the meandering channel are delineated using ArcGIS, as previously seen in Figure 8. Delineation of the bank lines were undertaken for every time-step in each experiment. Overlaying the bank lines through time was also completed in ArcGIS; the resulting outputs can be seen in Figure 32. The layering in ArcGIS was set up so that subsequent (later) time-steps appeared on top of the previous time-step layers. Subsequently, the two most visible bank lines in Figure 32 correspond to the initial bank lines (black in colour) and the bank lines at the end of the experimental runs (blue in EXP A and B, and lavender in EXP C). All the other time-step bank lines are present; however, they are just hidden under later time-step bank lines. In this section (and throughout the remainder of the thesis), the distinction of bank migration direction will be noted as “longitudinal” for downstream migration (x-direction in Figure 6) and “lateral” for transverse migration (y-direction in Figure 6).
The initial movement of the bank lines between the start of the experiments and the end of the first time-step (10 min for EXP A and B, and 30 min for EXP C) occur throughout the channel along both the inner and outer banks. This was expected as the initial channel geometry was a rectangular cross section and with the introduction of the flow, slumping of the banks throughout the flume occurred. The slumping of the top of the banks on both sides is clearly seen in the cross sectional plots at apex 2 in Figure 18.

The least amount of bank migration occurred in EXP A, with the majority of the movement occurring due to the slumping of the banks during the first time-step. Some of the largest slumping occurred along the
inner banks, which is not representative of a traditional erosion and channel growth profile. The only other time-step that provided some bank erosion in the meandering channel occurred after 60 min. After 60 min in EXP A, the outer bank at all three apexes migrated laterally. Some slight movement laterally (y-direction) occurred directly at apex 1 and 2, while some longitudinal migration occurred slightly downstream of apex 3 (x-direction). The total migrated distance of all three was very similar and relatively minor. Comparison of apex 2 (Figure 18 a) shows little difference at the outside bank between 40 min and 120 min. This is similar to the amount of bank migration at the other two apexes in the channel.

Greater bank migration throughout the meandering channel occurred in EXP B. Minor bank slumping occurred after the first time-step in this experiment, but EXP B also experienced continuous bank migration as opposed to EXP A. Distinguishable erosion occurred at 10 min, 20 min, 30 min, and 90 min. During the initial slumping of the banks in the first 10 min, a large amount of erosion also occurred immediately downstream of apex 1, moving the banks longitudinally downstream. This is seen in Figure 32 (b) as the banks at 10 min (orange line) move longitudinally downstream of the initial bank location (black line) from near the apex of the first meander along the channel down past the inflection point. A similar pattern occurs at the second apex, as the banks at 10 min move longitudinally downstream from the meander apex through to the inflection point. This is believed to be erosion as opposed to slumping because of the little slumping occurring throughout the rest of the channel. This same longitudinal erosion after 10 min can also be seen downstream of the third meander, but at this location it is more localized near the inflection point. Subsequent erosion at the first meander occurred after 20 min, with some minor lateral and longitudinal erosion occurring just after the apex. The localized erosion at the inflection point after meander 3 continued during time-step 2, with a slight longitudinal downstream movement right at the inflection point. After 30 min, some further erosion at apex 1 occurred, there was some minor erosion laterally just upstream of the erosion that occurred after 20 min. Further notable erosion didn’t occur in the meandering channel until after 90 min. After 90 min all three meanders witnessed some bank migration. Apex 1 and 2 moved slightly downstream in a similar fashion to what occurred after the initial time-step. The movement was not as severe as the first time-step, but the location was very similar; a longitudinal shift downstream from the meander apex to the following inflection point. Some longitudinal downstream migration of the inflection point after the third meander was also observed after 90 min; however, the migration became more localized at the inflection point through time.

The varying flow rates during EXP C caused the largest amount of bank morphology (Figure 32 c). Due to the hydrograph in EXP C, a substantial amount of channel evolution was observed during the rising limb of the hydrograph. At the initial low flow time-step, the bank migration is similar to what was
observed in EXP B. The predominant migration was in the longitudinal downstream direction. Very similar to EXP B, the longitudinal migration occurred from the apex through to the following inflection point. The first apex experienced the largest lateral migration. Lateral migrations at the apexes continue through the channel, but dissipated in amplitude in the downstream direction. During the rising limb of EXP C (50 min to 90 min) the banks continually migrated. The migration rates were similar between both the time-steps and the meander apexes. Similar to EXP B, the subsequent bank migration after the initial time-step almost exclusively migrates in the longitudinal downstream direction. The noted exception is after 90 min at apex 2, where a lateral shift occurring directly at the apex is observed. This coincides with the peak flow rate during EXP C, which caused near bank full conditions in the channel throughout the flume. Also during the peak flow (90 min), the three inflection points experience the largest amount of longitudinal downstream migration during the rising limb of the hydrograph. This is in agreement with field observations that have noted channel widening across the entire meander length at bank full conditions (Hughes, 1977; Marren et al., 2014).

At the time of the peak flow rate in EXP C, both banks had experienced some amount of movement from the initial channel geometry; however, the inner banks, especially at the apexes, had only experienced some minor erosion from the first flows. During the peak flow rate, continuous widening on both bank lines was not witnessed in the flume. Movement of the outer banks was noted at the peak flow rate and was seen through the whole meandering channel, aside from the apex at the third meander. During the initial carving process, the bottom of the channel was held true to the slope, but the bank heights weren’t uniform throughout. Even at a localized cross section, the inner and outer banks were not necessarily the same height, such as Figure 18 (a). This extra bank height is not the reason the inner banks did not erode, but may explain the reason the apex at the third meander was the only location along the outer banks that did not experience some erosion during the peak flows. The one location that was clearly at bank full was at the first meander apex on the outside bank, and although that bank did migrate, the migration at the apex peak was relatively minor. The armouring of the pool structure at the apex reaches a maximum during the rising limb of the hydrograph. This could explain the limited migration at the pool structures compared to the riffle structures.

During the falling limb of the hydrograph, little bank morphological development occurs. The erosion that does occur is relatively minor and occurs in limited locations. After 110 min, some lateral migration just prior to the peak is observed at the third apex. After 140 min, the same lateral migration just prior to the peak is observed at the second apex. The only other notable bank erosion occurs after 150 min after the third meander near the inflection point. The erosion on the falling limb prior to the apex could be attributed to the change in flow path after the large bank morphological adjustments to the preceding riffle
section during the rising limb. This adjustment causes the meanders to orient downstream, which is commonly seen in the natural environment (Dey, 2014). The downstream orientation applies to the skewness of the apex to be oriented down valley (Abad & Garcia, 2009).

The most interesting observation from the three experimental runs is the general trend to migrate longitudinally downstream. The downstream migration is clearly seen in EXP B and C (Figure 32). It was expected that the migration would move almost equally lateral and longitudinally. With the channel having a medium sinuosity, the direction of the velocity vector in the meander would result in equal amounts of longitudinal and transverse erosion, as shown in Figure 25. However, the migration observed in this experiment is more reminiscent of a low sinuosity channel where the apexes move downstream (da Silva, 2006, Fig. 15).

The results from the three experiments would be useful in comparison with existing models and the development of further planform morphology models. The most common planform models were developed around 1980 (Hasegawa, 1977; Ikeda et al., 1981) implementing a simple meander coefficient. An updated meander model (a model used to estimated meander morphological development) has recently been proposed that implements hydraulic erosion at the outer bank based on shear stresses (Motta et al., 2012a; Motta et al., 2012b). It would be expected that both models would provide reasonable results, as the limiting factor with the initial models (homogenous soils distributed vertically throughout the banks) is true within the flume. The initial models may even perform better for the present study as they often predict downstream meander migration and little growth of the meander amplitude (Motta et al., 2012a), which was witnessed in the experimental runs (Figure 32).

5.3.2 Thalweg Evolution

The thalweg also migrates during the experiment in conjunction with the planform morphological adjustments. The thalweg represents the deepest part of the channel and is often located along the outer banks at the apexes and crosses over the channel centerline in the riffle structure near the inflection point of the meandering pattern. Figure 25 shows the idealized thalweg in a meander channel. The thalweg was delineated by hand, which has been completed in previous research (Thayer & Ashmore, 2016). The delineation of the thalweg is completed by crossing the downstream contour lines perpendicularly. The contour lines used in the delineation process were the absolute elevations in the flume (such as Figure 26 a). The thalweg was defined through time using the individual time-step contour plots. The complete
figures for each experimental run is found in Appendix C, Figure 45, Figure 46, and Figure 47 and Figure 48 respectively.

The thalweg migration for EXP A, EXP B, and EXP C are shown in Figure 33, Figure 34, and Figure 35, respectively. Each figure shows the initial and final bank lines for that experimental run to provide context as to where the thalweg is situated within the evolving channel. The evolution of the thalweg has a similar time scale to that of the banks, but for simplicity, only a few thalweg time-step lines were plotted. The plotted lines represent the thalweg at an early, middle, and later stage of each experimental run.

![Legend](image)

*Figure 33: Thalweg development during EXP A at 20, 40, and 120 min (flow from right to left)*

Similar to the lack of bank morphological development in EXP A (Figure 32 a), the thalweg doesn’t adjust much through time (Figure 33); the initial thalweg development in the early time-steps remains very similar throughout the duration of the run. The thalweg generally moves laterally through time, but not by a considerable amount. The location with the largest amount of movement is at the fourth inflection point, just past the third meander. At this location, the thalweg shifts upstream shortly after the sorting phase as the sediment transport yield declined. The thalweg crosses over the first three meander inflection points near the center of the channel, but at the inflection points after the third meander apex the thalweg is shifted upstream of the centerline. The thalweg in EXP A has a downstream orientation at the apexes; this is clearly seen at the first and third apexes, but can also be seen at the second apex, as the thalweg is downstream of center at the inflection point. The downstream orientation at the apexes is similar to the pattern shown in Figure 25, but the location of the thalweg in Figure 33 remains more centered through the apexes as opposed to being located near the outer banks. This is due to the relatively minor bed form development (point bars and pool structures) at the apexes in EXP A (Figure 18 a).
The development of the thalweg in EXP B (Figure 34) is similar to that observed in EXP A. Although bank migration occurred in EXP B, the thalweg remained in a similar position through time. The development of the thalweg moves laterally through time, as can be seen at the first and second apex in Figure 34. The lateral growth at these two apexes occur upstream of the apex and little movement occurs downstream. The outward migration is associated with the pool development at the apex, as the pool moves laterally the thalweg too follows the lateral development. The delineated thalweg has a more substantial movement than the pool structure because the thalweg crosses the growing pool contours at a 90° angle while the upstream riffle structure remains unchanged (much slower development than the pool).

Although there is lateral growth upstream of the apex, a downstream orientation of the thalweg is seen at all three apexes, similar to EXP A and as observed in Figure 25. The location of the thalweg through the apexes in EXP B is in line with the pattern in Figure 25. The thalweg reaches the outer banks at all three apexes. The development of bed forms at the apexes, similar to Figure 18 (b), assist with moving the thalweg laterally. However, the thalweg through the apex at the third meander remains fairly close to the point bar. This is due to the location of the pool structure being downstream of the apex at the third meander (see Figure 26 b).

Figure 34: Thalweg development during EXP B at 20, 40, and 120 min (flow from right to left)

Figure 35: Thalweg development during EXP C at 40, 90, and 180 min (flow from right to left)
The development of the thalweg in EXP C was the most substantial of the three experiments due to the relatively greater and variable flows in the channel during the hydrograph. Unlike the previous experiments, some substantial development through time, even during the falling limb of the hydrograph, was observed in the thalweg. The thalweg grew laterally outwards with time, similar to EXP A and B. The majority of the growth occurs during the rising limb of the hydrograph, but some development on the falling limb was observed in the second and third meander apexes. The growth laterally occurs downstream of the apex at the first meander, but upstream at the latter two apexes. The first meander apex has an almost idealized thalweg development after the initial low flow. Following the erosion of the banks subsequent development of the thalweg occurs laterally. The upstream growth at the latter two apexes was a unique observation, as the general trend of the banks to migrate longitudinally downstream would suggest that the pools would move downstream too; however, it appears that the upstream riffle structure has a more significant impact on the thalweg development through the apexes.

The thalweg development of all three experimental runs resembled the pattern shown in Figure 25. The thalwegs had a downstream orientation at all apexes. The locations of the thalweg through the apexes were similar to the idealized pattern (Figure 25) in EXP B and C; however, EXP A had a more centralized thalweg line through the apex due to the lack of bed forms. The largest difference between the thalwegs in the experimental runs and the thalweg pattern in Figure 25 occurred in the riffle section, where the cross over is a lot sharper in the present runs. As opposed to a gentle cross over from the apex pool structure to the subsequent pool structure, the thalwegs in the flume is seen having an almost vertical line connecting the pool structures. This is easily seen in EXP B (Figure 34) between the first and second apexes and in EXP C (Figure 35) throughout the length of the channel. This could be due to the development time of the pool structures being faster than the riffles, and over time, the thalweg line would begin to resemble the pattern from Figure 25. Another possibility for the sharp thalweg cross over could be the bank migration at the apexes predominately moving longitudinally downstream without any lateral growth. As the upstream apex migrates downstream, the thalweg steepness increases as the entrance to the downstream apex remains in the same location. The other area of difference with the idealized pattern is the manner the thalweg enters the pool structures. The idealized pattern (Figure 25) shows the thalweg line entering the apex at a moderate angle, near the center of the channel. This was also observed at various times during the three experiments; however, the thalweg was also observed to have had a shallow entrance near the point bars. The shallow entrance is more common at the third apex (EXP A, B, and at the beginning of C) causing a large amount of thalweg growth longitudinally at the downstream end.
5.3.3 Sinuosity Morphology

As the banks migrate through time, the planform morphology can be quantified by the sinuosity changes. The sinuosity is described by Eq. 18 shown in Chapter 2. The meander wavelength may evolve, but the stream path centerline often grows at a faster rate, causing an increase in sinuosity with time. The sinuosity is measured across the entire meander section (one and a half meander wavelengths) from upstream of the first apex to downstream of the third apex. This meander section is highlighted in many figures, such as Figure 27. The sinuosity morphology is reported below in Table 10.

Table 10: Sinuosity changes with time for each experiment (following Eq. 18)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>0 Min</th>
<th>30 Min</th>
<th>60 Min</th>
<th>90 Min</th>
<th>120 Min</th>
<th>150 Min</th>
<th>180 Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP A</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>EXP B</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>EXP C</td>
<td>1.50</td>
<td>1.52</td>
<td>1.52</td>
<td>1.54</td>
<td>1.54</td>
<td>1.54</td>
<td>1.54</td>
</tr>
</tbody>
</table>

The sinuosity for EXP A and B began at the designed 1.50 and remained at this sinuosity throughout both experimental runs. The lack of sinuosity growth for EXP A could be due to the minor bank morphological developments observed (Figure 32a). The sinuosity through EXP B remained the same although there was some quantifiable bank migration occurring during the experiment. However, the movement of the banks do not appear to have had a significant enough impact on the channel centerline elongation to change the sinuosity. EXP C also had an initial sinuosity of 1.50. The initial low flow through the channel in EXP C caused substantial bank erosion which slightly increased the sinuosity. During the rising limb of the hydrograph in EXP C, the sinuosity remained unchanged at the lower flows, but increased at the peak flow conditions. The sinuosity grew the most at the peak flows. The increased sinuosity growth at the peak flow appears to be caused by the erosion in the longitudinal downstream direction at the inflection points (Figure 32c), causing the substantial elongation of the channel centerline through these areas. The channel sinuosity remained the same during the falling limb of the hydrograph, as expected.

Sinuosity of a sine-generated channel is restricted from being 1.0 (straight channel) to 4.2, at which point the meander loops intercept each other producing an oxbow lake. The sinuosity value of 1.5, which was the initial value in all three experiments, would be considered a stream of medium sinuosity. The growth of medium sinuosity would be expected to grow at a faster rate than a stream having low sinuosity but slower than a stream having high sinuosity because of the rate the meanders move laterally outwards (da Silva, 2006). The growth in EXP A and B was nonexistent over the experimental run time and only minor
sinuosity growth was noted in EXP C. Further tests with varying initial sinuosities would be required to determine if the growth rates from EXP A, B, and C fall in the expected range.

5.3.3.1 Braided Development

Although the sinuosity value didn’t increase during the falling limb of the hydrograph in EXP C, a different phenomenon was observed in the channel. After the peak flows resulted in the development of a large point bar at the second apex (Figure 27) with a large tail downstream, the subsequent time-steps slowly eroded the fines in the tail of the point bar until a subsidiary channel developed during the final time-step of EXP C ($t = 160$ min). At the time of the subsidiary channel development, the top of the point bar was above the water surface. The location of the secondary flow path is shown in Figure 36.

\[\text{Figure 36: Absolute view of the channel at the end of EXP C ($t = 180$ min): a) holistic view of the meandering section, b) enlarged view of apex 2 showing the development of a secondary flow path (flow from right to left)}\]
The primary flow path through the second apex remains through the pool structure around the outer bank, but the erosion of the point bar creates a more direct subsidiary channel between the pool structure and the downstream riffle structure. Figure 30 shows the material structure in the point bar that erodes later in EXP C ($t = 160$ min). The stability of the subsidiary channel is quite low, with a continuous growth in width as the exposed bar was eroded. Quantification of the growth of the secondary flow path is quite limited as it developed completely in the final 30-minute time-step of EXP C. However, qualitatively, the subsidiary channel grew laterally, primarily eroding the exposed bar during channel growth, with limited erosion of the permanent point bar. The instability of the exposed bar is common in braided rivers (Dey, 2014). The subsidiary channel also causes its own backwater effect. Previous research in the literature has attempted to define the threshold between a meandering channel and a braided channel (Carson, 1984; Ferguson, 1987; Henderson, 1961; Lane, 1957; Leopold & Wolman, 1957; Millar, 2000) by any combination of the channel slope, discharge, sediment properties, Froude Number, and vegetation. Analysis of this threshold will not be undertaken, as it’s outside the scope of this thesis, but the observed subsidiary channel development was quite remarkable. The single development of a subsidiary channel at a localized spot in the flume also isn’t indicative that the whole channel could be described as braided. According to Bristow and Best (1993), sand beds may exhibit braided characteristics during low flow scenarios. The development in the flume during EXP C would fall in this category, as the flow rate during the final time-step is almost half the flow that went through at the peak of the hydrograph.

5.4 Comprehensive Analysis

Analysis up to this point has focused on the individual components measured during the experimental runs (i.e., sediment transport rates, bed morphological development, and planform morphological development). However, further investigation is required to understand the inter-relationships between the fluvial processes occurring in the channel.

The comprehensive data is plotted in Figure 37 (EXP A and B) and Figure 38 (EXP C). The figures are focused on the second apex; this helps reduce the number of data points in the figures and apex 2 is the least impacted by the inlet and outlet weirs. Additional plots are found in Appendix F (Figure 88 and Figure 89) which provide the data for all three meander apexes in each experiment. The data in the figures combine the adjustments of bank morphology, bed morphology, and sediment transport rates with time. There are two black sediment lines in Figure 37, the lower is representative of EXP A (dashed line) and the higher line represents EXP B (solid line). Each plotted line shows the cumulative morphological
adjustment or sediment transport, meaning steep sections show the largest changes, while flatter slopes on the lines are indicative of little sediment yield or morphological development.

Figure 37: Interaction between sediment transport, bed morphological development, and planform evolution in EXP A and B (focused at apex 2) (A2 refers to EXP A at apex 2; B2 refers to EXP B at apex 2)

The results from EXP A and B in Figure 37 show considerable similarity even though the flow rates differed for the two tests. The development of the bed and banks is primarily completed in the early stages of the runs (e.g., \( t = 30 \text{ min} \)). For EXP A, only minor bed forms developed. As such, the slumping of the banks provided the majority of deposition of sediment on the bed. The slumping banks also caused the primary bank migration; some additional longitudinal downstream movement occurred after 60 min. These small morphological developments in the bed forms and planform also match up with the low sediment output measured in EXP A. Conversely, substantially more sediment yield and morphological development occurred in EXP B. The bank and bed morphology was similar to EXP A in that it rapidly developed in the first few time-steps before levelling off. The banks reach equilibrium while the bed continued to develop through the first 30 min. The sediment yield was also primarily completed within the first 30 min of EXP B as well; around 70% of the total sediment yield exits the channel in the first three time-steps. The slow increase in point bar height in EXP A is representative of the relatively long sorting period, compared to the point bar height for EXP B, which is very sharp in the first 20 min (relatively shorter sorting phase in EXP B) before levelling off. The quick sorting period in EXP A and B
where the largest sediment transport rates and morphological changes occurred follow observations noted in previous field studies, in which they noted that the final equilibrium position of an alluvial channel will occur in a short time (Church & Ferguson, 2015; Leopold & Langbein, 1962; Simons & Richardson, 1966). In the case of EXP A and B, the point bar deposition plots at apex 2 correspond most accurately with the sediment yield through time, while the banks reached equilibrium almost immediately. Figure 88 in Appendix F shows a similar trend with the other two apexes.

The large-scale differences between the morphological development and the sediment yield is due to the density of the sand. Small volumetric changes (primary vertical axis) represent a greater mass of sediment exiting the channel. This is why the difference between the morphological developments in EXP A and B is small (~1 cm), but the sediment difference so large (10 kg).

The results for EXP C, shown in Figure 38, were similar to the previous two tests at the initial low flow time-steps. The banks and bed experience an immediate development after the first time-step (i.e., t = 30 min) and then remain unchanged until the flow rate is increased during the rising limb of the hydrograph; this trend is also observed with the sediment transport. The resulting increase in flow rate causes a steady rise in sediment yield, longitudinal bank migration downstream, and point bar deposition. However, the lateral migration at the bank remains unchanged through the rising limb until a sudden lateral surge at the peak flow rate. After the peak flow, the depth of the point bar remained unchanged; however, further development is noted (Section 5.2.1 and 5.2.2), but the maximum deposition height remains near the same position during the falling limb (Figure 18 c). The longitudinal migration increases further slightly during the second time-step of peak flow rate before levelling off through the remainder of the hydrograph. During the falling limb of the hydrograph, the only morphological factor that slowly increases with the minor sediment yield is the lateral bank migration. While the migration is limited, it does gradually increase even though the flow rate is decreasing.
Figure 38: Interaction between sediment transport, bed morphological development, and planform evolution in EXP C (focused at apex 2) (C2 refers to EXP C at apex 2)

The results of the bank migration is unique once displayed against each other in Figure 38. During the rising limb of the hydrograph, the longitudinal downstream erosion is predominant while little lateral erosion occurs until the peak flow is reached. At the peak flow rate (90 min), the lateral and longitudinal erosion occurs at the same rate. During the falling limb, there is no longitudinal erosion and only some minor, but continuous lateral erosion at the apex throughout the falling limb. The high longitudinal erosion of the banks appears to cause the relatively higher sediment transport rates during the rising limb of the hydrograph, while the minimal and slow lateral erosion at the apexes cause the minor sediment yield during the falling limb. The erosion at the apexes during the falling limb of the hydrograph could just be a response to the high longitudinal erosion upstream or it could be representative of a dynamic response of the channel to varying flow rates. Further tests would be required to see if the witnessed incident is a reoccurring event.

The predominant amount of morphological development occurred on the rising limb of the hydrograph. The stream morphology has reached about 85% of its final development, and sediment yield by 90 min. This illustrates the impact of the rising limb of the hydrograph on the channel and its morphological response. This finding matches up with the hysteresis effect noted earlier (Figure 11) and the impact the rising limb of a hydrograph, such as spring runoff, can have on a natural system.
The longitudinal erosion clearly lines up very closely with the sediment yield with time, but the point bar deposition also grows at a similar rate with the sediment yield. However, examining the results of EXP A and B in addition to EXP C, the point bar deposition is the only plot that resembles the pattern of the sediment yield. This finding is useful for field studies, as it suggests that the presence of stability in bed forms would also suggest sediment equilibrium and vice versa.

A hysteresis analysis of the comprehensive data is provided in Figure 90 in Appendix F. Both the sediment transport rates and point bar deposition exhibited a clockwise hysteresis. The lateral migration data didn’t demonstrate any hysteresis trend. The longitudinal migration downstream exhibited a figure eight hysteresis, with the peak movement occurring at the high flow rate on the falling limb of the hydrograph. The data used in this analysis was taken from the second apex in the channel.

The comprehensive analysis of the three experimental runs (Figure 37 and Figure 38) matches previous field studies, showing channels attempt to reach equilibrium as quickly as possible (Church & Ferguson, 2015; Leopold & Langbein, 1962; Simons & Richardson, 1966). EXP A and B experienced a large amount of sediment yield, bed development, and channel morphology during the early time-steps of the runs (30 min) before tapering off; this is also observed at the beginning of EXP C. Additionally, EXP C observed a continuous growth of sediment yield, bed form, and bank development during the rising limb of the hydrograph as the channel adjusts to the increasing flow rates. The subsequent falling limb of the hydrograph has much less morphological change and sediment output as the channel has sufficiently developed to handle the lower flow.

The processes between the two different steady flow rates didn’t differ a considerable amount aside from the bed development. The channel sinuosity remained the same (Table 10) and the erosion process of the banks followed a similar trend. The bank migration adjusted longitudinally and laterally at the initial time-step, with only minor development observed afterwards. The bed development was also primarily completed within the first 40 min of both EXP A and B, but the level of development between the two studies varied significantly. EXP B saw much more development, but this may suggest the threshold for sediment entrainment in the experimental set up occurs somewhere between 0.8 L/s and 1.1 L/s.

In contrast, a very different development and process procedure was observed in the unsteady event in EXP C compared to the steady flow events. The sinuosity of the stream changed as the flow rate increased and the bank erosion followed a similar trend. The sinuosity experienced some growth after the first time-step and then a sudden increase at the peak of the hydrograph. The increase at the peak is something the steady state tests would have difficulty replicating, as any changes would only be noted in the first time-step. Similarly, the continual longitudinal erosion of the banks on the rising limb of
hydrograph would be difficult to replicate with the steady flow tests. These large longitudinal erosion rates influence the lateral bank erosion on the falling limb, showing a slow but steady increase that can’t be replicated with the steady flow tests. However, the bed development was more similar to the steady flow tests; continual growth in the initial time-steps was observed with the only difference being the duration of growth. The bed development process continued for a longer time than the steady flow during the rising limb of the hydrograph, but the rate of growth wasn’t as significant after the initial development. This suggests that planform processes were more affected by the unsteadiness of the flow than bed form development. The inability for steady flow experiments to catch the planform processes under unsteady flow shows the need for further testing with variant hydrographs and the implementation of unsteady flow into hydraulic models to accurately assess the bank migrations to variable flow through time.

5.5 Effects of Unsteadiness

The changing flow during the unsteady event also causes a dynamic sediment yield and morphological development during the unsteady event. This is clearly seen when examining the inter-relationship data in Figure 37 and Figure 38. After the initial sorting period, the two steady state experiments witnessed little sediment transport and morphological change. However, continual growth in erosion and sediment yield was observed in EXP C as the flow rate changes. The use of steady state data cannot accurately detect these continual changes. The volume of water discharged through the flume in EXP B equaled the volume of water from the hydrograph in EXP C, but the results were quite different; much more bank migration and sediment yield were observed in EXP C. The large variance in sediment yield between these two experimental runs was previously discussed in section 5.1.1. These differences were due to the effect of unsteadiness from the changing flow rates in the experimental hydrograph.

The effect of unsteadiness has been previously investigated. This previous research has led to the development of the unsteady flow parameter (Bombar et al., 2011; Graf & Suska, 1985; Lee et al., 2004; Yen & Lee, 1995). The unsteady flow parameter, $P$, can be defined as:

$$P = \frac{h_p - h_0}{\tau_d u_0}$$

Equation 29
Where $h_p$ is the flow depth at the upstream end of the channel at the peak of the hydrograph, $h_0$ is the initial flow depth at the upstream end of the channel, $t_d$ is the duration of the hydrograph, and $u_{*0}$ is the initial shear velocity at the upstream end. A second equation to describe the unsteady flow parameter was proposed by De Sutter et al. (2001) that only includes the rising limb of the hydrograph in the equation formation. Bombar et al. (2011) also developed a unique equation for the unsteadiness parameter that includes the velocity of the flow.

Previous researchers, who note that regardless of the size or duration of a hydrograph, an increase in sediment transport loads is expected to coincide with an increase in the unsteadiness of the flow (Bombar et al., 2011; De Sutter et al., 2001), highlight the importance of understanding the effect of unsteadiness. This increase in sediment transport yield is highlighted in Figure 39 with the data from the present research. Figure 39 shows the amount of sediment yield from the channel in each experimental run after the initial sorting and bed development phase. The degree of bank erosion after the initial development phase is shown in Figure 40.

![Figure 39: Sediment yield after the initial sorting phase ($t = 30$ min)](image-url)

Figure 39: Sediment yield after the initial sorting phase ($t = 30$ min)
Figure 40: Planform bank erosion after the initial sorting phase ($t = 30$ min)

The increase in flow rate between the two steady state show an expected increase in the sediment yield (Figure 39) and bank erosion (Figure 40). However, the unsteadiness in EXP C causes the sediment yield and bank erosion to increase exponentially from EXP B. This is due to rising limb of the hydrograph causing substantial sediment transport and bank erosion during each time-step of the rising limb of the hydrograph in EXP C (Figure 38). The impacts of the unsteady flow on bank erosion was previously discussed in Section 5.4. These figures help visualize the need for understanding the impacts of unsteadiness and how to quantify its effects on sediment transport rates and morphological adjustments. Unfortunately, little data exists on bank erosion in alluvial meandering streams under unsteady flow conditions; in fact, the only quantifiable data was gathered within the present research. The data points obtained in this research are limited and currently cannot provide any reliable feedback. Further testing within the flume is required before any comparisons between unsteadiness and bank morphology can be drawn. Fortunately, enough previous studies have investigated the effects of unsteadiness on sediment transport rates. The data from this thesis can help develop the existing state of the science and provide valuable data on an unconfined alluvial meandering stream.

From Eq. 29, the unsteadiness parameter for EXP C was determined to be $4.26 \times 10^{-5}$. Using this in combination with the results from Bombar et al. (2011), the combined data set is shown in Figure 41. Where the y-axis represents the dimensionless total bed load (Equation 28).
The data from EXP C fits in with the previous data set from Bombar et al. (2011). However, the same issue arises that was noted by Bombar et al. (2011) in that Figure 41 contradicts what is observed in nature; any increase in magnitude on the hydrograph would correspond with an increased sediment transport yield (Bombar et al., 2011; De Sutter et al., 2001). Figure 41 shows the inverse of this concept, with an increase in unsteadiness causing a decrease in total bed load. Although the data required for the other unsteadiness parameter equations (Bombar et al., 2011; De Sutter et al., 2001) wasn’t explicitly measured during EXP C, a close approximation of velocities can be calculated using the data from Table 5. The data point from EXP C is also an outlier with the unsteadiness equation of De Sutter et al. (2001). But the data point does fit well with the unsteadiness definition proposed by Bombar et al. (2011), showing that an increase in unsteadiness also causes an increase in total transported bed load. Therefore, it is recommended that the unsteady flow parameter, $P$, would best be defined by the following equation (Bombar et al., 2011).

$$P = \frac{gS_0 - \left( \frac{V_p - V_0}{t_r} \right)}{g}$$

*Equation 30*

Where $S_0$ is the initial longitudinal slope of the bed, $V_p$ is the velocity of flow at the peak of the hydrograph at the upstream end of the channel, $V_0$ is the initial velocity of flow at the upstream end of the channel, and $t_r$ is the duration of the rising limb of the hydrograph. From Equation 30, the unsteady flow parameter for EXP C is 0.0054. The largest difference with previous studies (Lee et al., 2004) is that the...
sediment yield increments were observed to decrease as the unsteadiness increased (leveled off), while the data point from Eq. 30 in conjunction with previous research (Bombar et al., 2011), show that as unsteadiness increases the sediment yield increases substantially (towards infinity).

The data from Figure 39 and Figure 40 are shown in a table format (Table 11) along with a predicted steady flow test carried out at a constant 1.45 L/s (the maximum flow rate reached in the real EXP C). Once again, the data is showing values after the initial sorting and development phase. The values obtained for the steady 1.45 L/s test were linearly extrapolated from the first two steady state experiments.

Table 11: Sediment yield and bank erosion for EXP A, B, and C and a predicted outcome for EXP C after the initial sorting phase

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Maximum Flow Rate (L/s)</th>
<th>Sediment Yield (g)</th>
<th>Planform Bank Erosion (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP A</td>
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<tr>
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<td>0.019</td>
</tr>
<tr>
<td>EXP C</td>
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<td>14404</td>
<td>0.188</td>
</tr>
<tr>
<td>Predicted Steady Flow EXP C</td>
<td>1.45</td>
<td>7764</td>
<td>0.0295</td>
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</table>

The data for the predicted steady flow tests in Table 11 was calculated very crudely and it provides a basis for analysis versus some of the results and findings of Lee et al. (2004). The measured sediment yield in EXP C was 14,404 grams, while the predicted was 7,764 grams. This shows that the measured was 1.86 times the predicted value from a steady flow experiment. This data point fits in well with the findings of Lee et al. (2004) regardless of the unsteadiness parameter used. Lee et al. (2004) showed a uniform ratio across all unsteady flow parameters, that the magnitude of sediment yield from an unsteady event was near 1.6 times that predicted by a steady event. Although robust, the data from this thesis seems to agree with previous findings, that steady flow events can be used to estimate sediment transport rates for an unsteady event (Lee et al., 2004).

The difference between measured and predicted values in Table 11 for the sediment yield is smaller in scale than the bank erosion. The findings suggest that steady flow events can be used to predict sediment yield during an unsteady event, but much more research is required to see if the same is true for bank erosion. At the very least, it appears that the adjustment coefficient will be much higher than 1.6, and the location of the erosion adjustment will also need to be carefully analyzed.
This section helps demonstrate the importance of investigating and understanding the effects of unsteady flow. The results from EXP C line up with previous studies regarding sediment transport. It is suggested that the unsteady flow parameter be defined through Eq. 30, as it provided the most realistic data to what is observed in nature. The extrapolation of data from the steady flow tests (EXP A and B) suggest that there is a correlation between sediment transport under steady flow and unsteady flow conditions. The finding is in agreement with previous research (Lee et al., 2004), that the measured sediment yield under unsteady conditions is around 1.6 times the predicted value using steady flow conditions. This is useful for estimating expected sediment outcomes under unsteady flow using steady flow conditions, as the findings are unrelated to the unsteady flow parameter. However, further research and data is required to investigate these effects on planform adjustments. Currently, the only viable data set is provided in the present research, but further data is required before any conclusive outcomes can be drawn. It is expected that an increase in unsteadiness will also correspond with an increase in bank erosion, similar to the expected outcomes with sediment yield. The ability to measure bank erosion from steady flow conditions is more complicated, as the factor of adjustment is anticipated to be high (higher than the 1.6 for sediment transport) and the location of the increased erosion is also a complex phenomenon.

The impact of unsteadiness on the bed development was not examined due to limited data (much like the bank erosion) and the process of development was fairly similar to the steady flow tests (see Section 5.4). This preliminarily suggests that the effects of unsteadiness are less pronounced on bed development processes.
Chapter 6: Conclusions and Recommendations

6.1 Conclusions

A sand basin flume at the University of Guelph’s Water Resources Engineering Laboratory was used to investigate the impact of discharge on sediment transport rates and channel morphology in an unconfined alluvial meandering channel. Three experimental runs with various flow rates through a medium sinuous meandering channel were completed. Two of the tests were with steady flow and the third was completed with a uniform quasi-unsteady state hydrograph to investigate the effects of unsteady flow on the morphological response of the channel.

The data obtained from the experimental runs and the results of this research were instrumental in answering the initial objectives of this thesis.

1. The development time of the channel to different flow rates

Examining the two steady state experimental runs provided the best opportunity to analyze the development time of the channel and its relation to discharge. Unfortunately, EXP A saw few bed forms and little development, but considerable bed and planform development was observed in EXP B. The development of the channel was quantified using the data from the point bar deposition. As depicted in Figure 20, the development of the channel showed large development at the initial time-step before decaying exponentially as the channel developed to equilibrium conditions. It was found that all three apexes developed in this manner, with the development being completed in 40 min; subsequent adjustments occurred after 40 min, but were negligible in relation to the overall development of the channel. Previous field observations noted that channels try to achieve equilibrium conditions as quickly as possible (Church & Ferguson, 2015; Leopold & Langbein, 1962; Simons & Richardson, 1966), which was clearly observed and quantified in EXP B. The development of the channel bed and banks also occurred quickly with the changing flow rates on the rising limb of the hydrograph in EXP C. The short time to equilibrium has also been noted in previous flume experiments (Song et al., 2016).

2. The response of the sediment transport rate to varying flow rates

The sediment transport rate increased with the increasing flow rates of the hydrograph in EXP C. The sediment transport behaved in a clockwise hysteresis fashion in response to the varying flow rates (Figure 11). The sediment yield under the hydrograph is substantially larger than those measured with a steady flow at the average discharge of the hydrograph. The under representation of sediment yield from a steady
flow equivalent has previously been highlighted (L. Wang et al., 2015), with these results further emphasizing the need for experimental studies working with unsteady flows. In conjunction with the development time in EXP A and B, the sediment transport rates decreased exponentially in the steady flow tests. However, it wasn’t an instantaneous exponential decrease, the sediment transport rates fluctuated near each other in the sorting phase of the channel before decreasing. The sorting phase of EXP A took longer than EXP B, even though the flow rate was less. This finding was in agreement with previous research (Guney et al., 2013; L. Wang et al., 2015), with the likely cause of a more rapid sorting phase with the high flow rate being that all the sediment classes were available for transport.

3. **Bed and planform morphological development of a meandering channel to varying conditions**

The development of a pool riffle structure with the pools occurring at the meander apexes and the riffle structures near the crossover points was observed in the channel in all runs. The overall sediment distribution on the bed and morphological responses were similar to the general understanding of the morphological processes occurring in a river (Figure 25). The point bars grew in height and outwards (transverse) as the flow rate increased during the rising limb of the hydrograph. The largest changes to the point bar occurred just prior to the peak flow (Figure 86). Subsequent adjustments during the falling limb were minimal, with the largest changes being the deposition of sediment in the pool structure. A general fining of the bed was observed at the channel apexes, but this was associated with large amount of fines in the point bar while the thalweg experienced coarsening (Figure 22). This armouring effect in the thalweg at the apex was in agreement with previous research (Guney et al., 2013).

The largest amount of adjustments to the meandering planform morphology also occurred during the rising limb of the hydrograph. The bank migrated continuously with the increasing flow rate, but the migration occurred predominately in the longitudinal downstream direction. This was contrary to general trends, as it was expected to grow laterally outwards in conjunction with the downstream migration. During the falling limb of the hydrograph, little bank erosion was observed. Minor bank erosion occurred in the lateral direction. The overall morphological response caused the meanders to orient downstream, which is commonly seen in nature (Dey, 2014). The sinuosity of the channel only changed (increased) during the rising limb of the hydrograph (Table 10).

4. **Comprehensive evaluation of channel morphology with respective to sediment transport, bed development, and planform morphological development**

Combing the results from the various morphological analyses provided valuable feedback. A large amount of adjustment occurred in the first few time-steps of the two steady state experimental runs, before subsiding considerably in the later time-steps (Figure 37). These results were in agreement with the
data obtained at the point bars (Figure 20), with the majority of development occurring in the early time-steps before the rate of development decreased exponentially. Similar development at the initial low flow time period was observed in EXP C. The development then remained constant until the discharge began to rise with the hydrograph. The longitudinal migration of the banks and the point bar growth occurred simultaneously with the increasing flow rate and sediment yield. The banks also grew laterally during the rising limb of the hydrograph but occurred with sudden surges at two time-steps. After the peak flow, the sediment yield, longitudinal bank migration, and point bar growth subsided, while the lateral migration increased steadily but the erosion was minimal in relation to the overall development. During EXP C, a clockwise hysteresis of sediment transport rates and point bar growth was observed in the channel. A figure-eight hysteresis was observed in EXP C for the longitudinal bank migration downstream; while the lateral migration outwards at the banks demonstrated no hysteresis correlation.

5. **Analyze the effect of unsteadiness in a meandering channel**

The results from EXP C were compared with the findings from EXP A and B to further develop the knowledge on the effects of unsteadiness and draw parallels with previous research (Bombar et al., 2011; De Sutter et al., 2001; Graf & Suska, 1985; Lee et al., 2004; Yen & Lee, 1995). The large impact of unsteadiness on sediment transport rates and bank morphology is shown in Figure 39 and Figure 40, in which EXP C experiences a substantially higher amount of development than the steady flow tests. To quantify the effect of unsteadiness, analyses of three different equations representing the unsteady flow parameter were undertaken. It was found the equation (Eq. 30) developed by Bombar et al. (2011) was the most accurate for the data obtained from the present research. The ability to quantify morphological outcomes from unsteady events using steady flow was also investigated. The data obtained from EXP C agrees with the results of previous researchers (Lee et al., 2004), in that the sediment transport is near 1.6 times that estimated by a corresponding steady flow. The data from EXP C is robustly compared to an anticipated value obtained by extrapolating the data from the two steady flow tests. It is anticipated that a similar coefficient linking planform erosion from unsteady events to steady events could also be conceived in a similar manner to the sediment transport rates; however, further experimental research is required to develop a better understanding of the complexity of erosion in unconfined alluvial meandering streams.

6. **Investigate the accuracy of hydraulic modelling software to model the morphological response of an unconfined alluvial meandering channel to various discharge events**

HEC-RAS was utilized to investigate the accuracy of the morphological response of an unconfined alluvial meandering channel to various discharge events within the model. Currently, HEC-RAS is
limited to a 1D sediment transport model, as such, no bed forms can properly be modelled with the software. Planform adjustments by way of bank slumping is possible in HEC-RAS, however, the accuracy of the results were poor. This was due to non-cohesive soil in the flume and the inability to properly model the bank material in HEC-RAS. However, the model does provide an examination of the sediment transport measurements. The model was unable to accurately predict the large sudden changes associated with the sorting period or the rising limb of the hydrograph. This lack of sediment yield could be attributed to the inability of the model to accurately detect the morphology, especially the bank erosion, as this provided much of the sediment supply in the laboratory channel. It was found that the Engelund & Hansen (1967) sediment transport formula performed the best of the two methods tested. It was able to perform well for the entire duration of EXP A and produced accurate results at the latter time-steps near equilibrium in all three experimental runs. The other interesting output from the HEC-RAS models was that the Meyer-Peter & Muller formula produced a clockwise hysteresis of sediment transport rates while the Engelund & Hansen formula produced a single-valued line hysteresis.

In addition to addressing the goals of the present research, of few unanticipated findings were noted. These findings included the relationship between sediment size and the hysteresis of sediment transport rates, and the development profile of the point bars. It was observed that the sediment yield during the two steady state tests saw a fining trend as the experiment time increased, but in EXP C where the flow rate varied, a quantifiable observation was made. Figure 12 (c) shows the fining trend in EXP C at the low flow rates, but as the flow increases, so does the fractional bed load of the larger sediment classes. This suggests that the increasing flow rates not only cause large morphological evolution and sediment yield, but the type of sediment transported also has an increased proportion of larger particles. This finding could be extremely useful when forecasting sediment transport in rivers and the temporal effects that the natural flow cycle has on the system. The other interesting result pertains to the development of the point bars at the meander apexes. The sediment deposited at the apex caused the point bars to grow in height and outwards (laterally) (Figure 18), but the growth in height was limited to the flow depth in the channel. The location of the transition point between point bar and pool also moved laterally towards the outer bank, but at a slower rate than the point bar. The caused the sediment to become unstable and began to develop a secondary step in the point bar. The angle of steepness of the point bar before becoming unstable was found to be 25 degrees; this was noted in both EXP B and C. This finding provides further empirical evidence, first noted by Kawai & Julien (1996), that the side slope angle of the point bar is constricted to the angle of repose of the bed material.

In total, the research completed was able to address the objectives set out at the beginning of the thesis, while some additional and interesting observations formed additional contributions. This research is
valuable for the growth of river engineering and fluvial hydraulics and provides some of the earliest findings completed in an unconfined meandering channel flume experiment. This data and research will be useful for the improvement and development of modelling programs, such as HEC-RAS. The quantifiable results obtained will also be useful in the development of new sediment transport equations (or validation of existing ones), morphological responses, and channel development equations. The impact of this research to river mechanics and engineering disciplines will enable a better design and management of future stream restoration and channel design projects.

6.2 Recommendations for Future Work

The results obtained in this thesis provide valuable and notable findings to the field of river mechanics. The experimental research completed in EXP C is believed to be the second flume study that analyzes the effects of unsteady flow on a completely unconfined channel (bed and bank) (van Dijk et al., 2013). In addition, the experimental runs with steady flow (EXP A and B) also provide additional valuable results to compare with previous unconfined channel and steady flow studies (Table 3), while building on recent previous research (Song et al., 2016). Despite recent advances, further research in this field is required in the future. The enormity of laboratory studies completed in confined channels (Table 1 and Table 2) far outweigh the number of laboratory studies on unconfined channels. Similarly, the number of straight flume experiments are much greater than sinuous channel studies. As such, future laboratory experiments completed in a laterally unconfined meandering channel would provide useful findings.

The first recommendation is to continue utilizing physical experiments, such as flume experiments, to evaluate and quantify sediment transport and morphological adjustments. These studies are useful in the development and improvement of predictive equations associated with the fluvial processes. These new equations assist in improving the accuracy of modelling software available to practitioners working in the river mechanics field.

The flume in the University of Guelph’s Water Resources Engineering Laboratory provides the opportunity for future studies to expand on recent findings and discover new breakthroughs in river hydraulics. The findings of this current research lead to some general recommendations for future studies. Additional studies with varying discharge, channel sinuosity, and slopes would be beneficial to add to the quantity of studies and reveal general trends. It would also be recommended that the tests be completed multiple times to ensure the data results are repeatable; this would’ve been useful when evaluating the existing equations (Figure 15) to weed out which measured data point at 0.8 L/s is the outlier. The
varying flow rates could be analyzed with skewed hydrographs, to analyze the impact that the hydrograph time to peak has on the morphological response. This would be useful in evaluating the response to urbanization and land use as the discharge events become flashier. Adjusting the channel with varying deflection angles (i.e., sinuosity) would enable the examination of how the channels migrate; it would be interesting to distinguish the boundaries for the three planform morphological phases (low sinuosity having a primary downstream migration trend, high sinuosity having transverse expansion trend, and a medium sinuosity have equal parts transverse expansion and downstream migration) (da Silva, 2006, Fig 15) with quantifiable physical data.

In terms of findings from this thesis, there are a few points that are recommended to be further investigated. The response of large morphological changes occurring simultaneously with high sediment discharge was found in EXP C. Additional confirmation of this finding would be valuable. A longer simulation time with a repeating hydrograph would allow future research to examine the impact of the morphological changes and answer the following questions: do the bed forms return to their original position at after the conclusion of the hydrograph?, do large morphological adjustments still occur with high sediment discharge? Longer simulations in the flume could allow for comparison with real reaches in nature and how they adjust to annual flow patterns. Further analysis of fractional bed load mobility is required to confirm that larger particles are transported downstream during the rising limb of the hydrograph in conjunction with hysteresis effects. Future study on the impact of this finding in other disciplines like environmental science and ecology would be very interesting. Finally, the analysis of bed gradation adjustments through time would be valuable. The use of the existing photos from the present research in conjunction with grain size delineation software (Adams, 2013; L. Wang et al., 2015) would be useful to quantify the armouring effects in the channel as well as highlighting the pool riffle structure. The quantification of the bed material also allows for further analysis of the predictive sediment transport equations and the possible development of a new transport equation more representative of these conditions.

The analysis of the existing transport equations is a bit crude, in that the number of measured data points is very low. Further measured data is required before any conclusive results can be derived. This would include additional experimental runs or the ability to accurately measure the $D_{50}$ of the available sediment for transport. The existing photos taken for DEM production could be coupled with additional software to produce surface distribution of the sediment similar to previous research (L. Wang et al., 2015). Currently the measured data comes from the sorting phase when lots of movement is occurring and the shear velocity equations already over-predict transport. It would be anticipated that this would also occur, possibly in an even higher magnitude, if the only adjustment to the equations occurred with the $D_{50}$. The
ability to investigate the sediment transport rate at a particular location and time in the channel, such as the apex of meander 2, would require further investigation and analysis techniques (Curran et al., 2015).

Additional modelling capabilities could be undertaken with the existing data from this thesis. HEC-RAS was utilized, but other hydraulic models could also be tested to analyze their accuracy. Open source software that attempts to model the planform and bed form evolution (Hasegawa, 1977; Ikeda et al., 1981; Motta et al., 2012a, 2012b) could be used to compare with the measured results. Alternatively, proprietary software commonly used by practitioners, such as Mike 21C, could be implemented to compare its performance versus HEC-RAS. Software being implemented today by practitioners would be valuable to analyze as it could directly contribute to advancing the capabilities of modellers and river engineers.

Additional research looking into any aspect mentioned above will help further the science and the understanding of the natural world. The most important part for the future of river mechanics and hydraulics is the continuing desire to learn more.
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Appendix A: Laboratory Data

Table 12: Measured flow rate data in EXP A

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<tr>
<th>Time (min)</th>
<th>Measured Flow Rate (L/s)</th>
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Table 13: Measured sediment transport data in EXP A

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Table 14: Measured flow depths at the apexes in EXP A

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Table 15: Measured flow rate data in EXP B

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### Table 16: Measured sediment transport data in EXP B

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|-----------|---------|-----------------------------|------------|---|---|---|---|---|---|---|
|           |         |                             | 4.75       | 2 | 0.85 | 0.425 | 0.25 | 0.15 | 0.106 | 0.075 | 0  |
| 1         | 2517    | 5.1                         | 527        | 801.2 | 591 | 272.7 | 199 | 66.3 | 43.2 | 11.1 |
| 2         | 3108    | 5.1                         | 646.1      | 918.6 | 899.6 | 217.9 | 289.3 | 79.6 | 42.2 | 9.1 |
| 3         | 2571    | 4.4                         | 505.1      | 788.9 | 596.5 | 336.8 | 242.2 | 58.3 | 42.7 | 8.8 |
| 4         | 1757    | 1.5                         | 301.9      | 518.6 | 407 | 243.1 | 182.6 | 59.5 | 32.2 | 10.4 |
| 5         | 1251    | 1.3                         | 211.6      | 366 | 304 | 173.9 | 130.6 | 37.4 | 22.4 | 3.6 |
| 6         | 391     | 0                           | 43.6       | 100.8 | 93.6 | 65.7 | 57.3 | 18.6 | 8.7 | 0.8 |
| 7         | 300     | 0                           | 22.5       | 70.3 | 79.2 | 57.7 | 45.3 | 16.8 | 7.8 | 0.3 |
| 8         | 56      | 0                           | 4          | 12.2 | 17.4 | 15 | 14.3 | 4.6 | 2.7 | 0  |
Table 17: Measured flow depths at the apexes in EXP B

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Table 18: Measured flow rate data in EXP C

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Table 19: Measured sediment transport data in EXP C

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Table 20: Measured flow depths at the apexes in EXP C

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Appendix B: Laboratory Set-up and Equipment

Figure 42: Experimental facility schematic (cross sectional view)

Figure 43: Initial carving of the channel (looking downstream) for EXP B
Figure 44: Sediment collection trap
Appendix C: Morphological Elevation Contour Plots

<table>
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<th>Time-step 0 (0 minutes)</th>
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<th>Time-step 8 (120 minutes)</th>
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*Figure 45: DEM with absolute contours for each time-step in EXP A (flow from right to left)*
Figure 46: DEM with absolute contours for each time-step in EXP B (flow from right to left)
Figure 47: DEM with absolute contours for each time-step in EXP C (0 min to 110 min) (flow from right to left); continued in Figure 48
Time-step 10 (120 min)

Time-step 11 (130 min)

Time-step 12 (140 min)

Time-step 13 (150 min)

Time-step 14 (180 min)

Figure 48: DEM with absolute contours for each time-step in EXP C (120 min to 180 min) (flow from right to left); continued from Figure 47
Appendix D: Morphological Elevation Development Plots

Figure 49: Development plot of morphological adjustments from initial bed for EXP A at $t = 10$ min (flow from right to left)

Figure 50: Development plot of morphological adjustments from initial bed for EXP A at $t = 20$ min (flow from right to left)
Figure 51: Development plot of morphological adjustments from initial bed for EXP A at $t = 30$ min (flow from right to left)

Figure 52: Development plot of morphological adjustments from initial bed for EXP A at $t = 40$ min (flow from right to left)
Figure 53: Development plot of morphological adjustments from initial bed for EXP A at $t = 50$ min (flow from right to left)

Figure 54: Development plot of morphological adjustments from initial bed for EXP A at $t = 60$ min (flow from right to left)
Figure 55: Development plot of morphological adjustments from initial bed for EXP A at $t = 90$ min (flow from right to left)

Figure 56: Development plot of morphological adjustments from initial bed for EXP A at $t = 120$ min (flow from right to left)
Figure 57: Development plot of morphological adjustments from initial bed for EXP B at t = 10 min (flow from right to left)

Figure 58: Development plot of morphological adjustments from initial bed for EXP B at t = 20 min (flow from right to left)
Figure 59: Development plot of morphological adjustments from initial bed for EXP B at $t = 30$ min (flow from right to left)

Figure 60: Development plot of morphological adjustments from initial bed for EXP B at $t = 40$ min (flow from right to left)
Figure 61: Development plot of morphological adjustments from initial bed for EXP B at $t = 50$ min (flow from right to left)

Figure 62: Development plot of morphological adjustments from initial bed for EXP B at $t = 60$ min (flow from right to left)
Figure 63: Development plot of morphological adjustments from initial bed for EXP B at t = 90 min (flow from right to left)

Figure 64: Development plot of morphological adjustments from initial bed for EXP B at t = 120 min (flow from right to left)
Figure 65: Development plot of morphological adjustments from initial bed for EXP C at $t = 30$ min (flow from right to left)

Figure 66: Development plot of morphological adjustments from initial bed for EXP C at $t = 40$ min (flow from right to left)
Figure 67: Development plot of morphological adjustments from initial bed for EXP C at t = 50 min (flow from right to left)

Figure 68: Development plot of morphological adjustments from initial bed for EXP C at t = 60 min (flow from right to left)
Figure 69: Development plot of morphological adjustments from initial bed for EXP C at $t = 70$ min (flow from right to left)

Figure 70: Development plot of morphological adjustments from initial bed for EXP C at $t = 80$ min (flow from right to left)
Figure 71: Development plot of morphological adjustments from initial bed for EXP C at $t = 90$ min (flow from right to left)

Figure 72: Development plot of morphological adjustments from initial bed for EXP C at $t = 100$ min (flow from right to left)
Figure 73: Development plot of morphological adjustments from initial bed for EXP C at $t = 110$ min (flow from right to left)

Figure 74: Development plot of morphological adjustments from initial bed for EXP C at $t = 120$ min (flow from right to left)
Figure 75: Development plot of morphological adjustments from initial bed for EXP C at $t = 130$ min (flow from right to left)

Figure 76: Development plot of morphological adjustments from initial bed for EXP C at $t = 140$ min (flow from right to left)
Figure 77: Development plot of morphological adjustments from initial bed for EXP C at t = 150 min (flow from right to left)

Figure 78: Development plot of morphological adjustments from initial bed for EXP C at t = 180 min (flow from right to left)
Appendix E: Bed Development

Figure 79: Bed development at apex 1 in EXP A

Figure 80: Bed development at apex 2 in EXP A
Figure 81: Bed development at apex 3 in EXP A

Figure 82: Bed development at apex 1 in EXP B
Figure 83: Bed development at apex 2 in EXP B

Figure 84: Bed development at apex 3 in EXP B
Figure 85: Bed development at apex 1 in EXP C

Figure 86: Bed development at apex 2 in EXP C
Figure 87: Bed development at apex 3 in EXP C
Figure 88: Interaction between sediment transport, bed morphological development, and planform evolution EXP A and B
Figure 89: Interaction between sediment transport, bed morphological development, and planform evolution in EXP C
Figure 90: Hysteresis effect of channel responses in EXP C