River Resilience Requires Sufficient Floodplains: Experimental Insights from a Novel Flume Study Investigating Meander Constriction

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Globally, riparian zones are in poor condition. Numerous anthropogenic watershed modifications negatively affect water quality, resiliency, and habitat diversity of river systems. Research on the effects of constricting meandering rivers is limited. This has led to few methods that optimize riparian zone widths in ways that maintain adequate corridors or floodplains to support natural river processes and protect public safety. The goal of our research was to determine the effects of constraining the floodplain of a meandering river. Specifically, we studied the effects of constraining the Bow River in Calgary where the floodplain corridor is currently facing extensive development pressures. To achieve these goals a mobile bed laboratory experiment was completed. The experiment involved developing and then constricting a gravel bed meandering river from an initially straight channel. Alfalfa was grown alongside the river and within the floodplains to provide necessary bank strength. During the experiment, sediment leaving the flume was collected and aerial images were captured to allow topographic and sediment transport analysis. Results showed that as alfalfa grew, bank strength increased, limiting meander evolution. Despite the relatively fixed meanders, findings suggest that floodplain constraints significantly reduce river-floodplain connectivity, alter a channels flow regime by increasing velocity and flow depth, increase sediment transport, and narrow channel widths. The results of this study will impact river management practices, emphasize creating room for rivers as a nature-based solution, and improve laboratory methods for investigations of meandering rivers.

Acknowledgments

I would like to acknowledge that this work was completed on the traditional territory of the Neutral, Anishinaabeg and Haudenosaunee peoples. The Hydraulics Lab at the University of Waterloo is situated on the Haldimand Tract, land that was promised to the Six Nations, spanning six miles on each side of the Grand River. This research also engages with areas in southern Alberta, located within the traditional territories of the peoples of Treaty 7, which include the Blackfoot Conferacy, the Tsuut'ina First Nation, and the Stoney Nakoda. The City of Calgary is also home to the Métis Nation of Alberta (Districts 5 and 6). As a non-indigenous person, I acknowledge the ongoing histories and impacts of colonialism on these lands and communities. I hope this work can contribute, in some way, to efforts of cultural preservation and land reclamation through the restoration of river systems and improved access to waterways.

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Huge thanks go out to everyone who helped with this project, specifically my supervisor Bruce MacVicar who guided me throughout the whole process. Jonathan Slaney who brought this project to life. Mark Hummel who made the experiments possible. Violet, Riley and the entire lab group who were instrumental in helping me complete the experiments, and last but by no means least my parents and Declan who supported me throughout it all!

Dedication

My thesis is dedicated to all the wild and winding rivers that shape landscapes, support ecosystems, and allow all life to thrive. I hope one day everyone can appreciate them as I do, and our greed and carelessness will no longer take their breath away.

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List of Abbreviations

Abbreviation	Description
Agisoft	Agisoft Photoscan Professional
LMR_expX	Living Meandering River Experiment #X
DEM	Digital Elevation Model
DoD	Difference of Digital Elevation Model
PVC	Polyvinyl Chloride
3D	Three-dimensional
EOS	Electro-Optical System
AutoCAD	Automatic Computer Aided Design

List of Symbols

Symbol	Description
Fr	Froude Number (-)
V	Velocity (m/s)
g	Gravitational Constant (m/s^2)
D_h	Hydraulic diameter (m)
Re_*	Particle Reynolds number (-)
Re	Reynolds Number (-)
ρ	Fluid Density (kg/m^3)
ρ_s	Sediment Density (kg/m^3)
μ	Dynamic Viscosity (N*s/m^2)
u^*	Shear Velocity (m/s)
D_{90}	Sediment Diameter of the 90th percentile (m)
v	Kinematic Viscosity (m^2/s)
D_{50}	Sediment Diameter of the 50th percentile (m)
τ	Shear Stress (N/m^2)
${\tau_b}^*$	Dimensionless Shear Stress (-)
${\tau_c}^*$	Critical Shear Stress (-)
γ	Specific weight of water (N/m^3)
S	Bed Slope (m/m)
R_h	Hydraulic Radius (m)
x_r	Length Scale (-)
x_p	Prototype Length (m)
x_m	Flume Model Length (m)
A_m	Drag Correction Coefficient (-)
R	Relative Density (-)
q_b	Volumetric Sediment Transport (m^3/s/m)

Chapter 1. Introduction

1.1 Motivation

Urban development would be easier if rivers were simple, stable, and static. However, rivers defy this, as they naturally migrate throughout their floodplains, reshaping landscapes over time. This mobility should not be viewed as a threat that needs to be controlled, but a vital process that creates ecological and social benefits. When rivers have the space they require there are many benefits including improved water quality, erosion control, enhanced biodiversity, increased resilience, flood protection, and enriched recreational opportunities (Arif et al., 2021; Drunpob & Chang, 2007; Han et al., 2023; Klijn et al., 2018; Lee et al., 2004; Luke et al., 2019; McKergow et al., 2016; Mundahl et al., 2023; Nelson et al., 2024; Rohde et al., 2006).

There is no doubt that maintaining and creating space for rivers improves the natural environment and benefits society. Despite this, riparian zones all over the world have faced and still face relentless pressures. Urban development and shifting land use have altered natural flood regimes, while forestry and agriculture have removed natural riparian vegetation. Historic engineering practices have confined rivers and disconnected them from their floodplains. Climate change has added greater uncertainty and new concerns to flood events. All these disruptions have one thing in common: human activity.

If we are the cause of these degrading riparian conditions, then we should be the solution. However, that solution is far from simple. Persuading powerful profit driven industries that shape environmental policies is tough. River systems evolve over decades, and when we do not fully understand the long-term consequences of constricting a meandering river's floodplain, it becomes easy to dismiss the damages as minimal and insignificant.

The scientific community has a strong understanding of the importance of riparian zones but less in known about the effects of constraining meandering rivers (Amini et al., 2020; Garcia Lugo et al., 2015; Nicoll & Hickin, 2010; Parsapour-Moghaddam & Rennie, 2018). Flume studies offer a valuable tool to investigate river processes by providing a tactile, physical representation of complex systems. Flume studies are often more cost effective, less disruptive to sensitive natural environments, and easier for researchers to observe and collect data from in varying hydraulic

situations. Beyond research, flumes are great educational tools, helping to engage a broader audience that can influence the environmental policies we need to protect our rivers. Flume studies have limitations, but when designed and executed effectively they might be able determine a long-term balance between river health, social benefits, and the constraints we impose on rivers.

1.2 Background

This research was completed in partnership with the City of Calgary, because they are concerned with maintaining the health of the Bow River. The Bow River is a low sinuosity gravel-bed meandering river in southern Alberta, that runs directly through the City of Calgary (Jackson Jr et al., 1982; Yu et al., 2025). The river is incredibly important to the city as it provides 60% of Calgary's drinking water and supports recreation and tourism (Calgary River Valleys, 2021). Despite its importance, the health of the Bow River is under threat, the city is currently facing extensive development pressures. Historically, the city has built along the river, as presented in Figure 1.



Figure 1. The Bow River running through the City of Calgary

Municipal guidelines set in 2007 recommend a 50-meter set-back for any future development along the Bow River (City of Calgary, 2007). However, this set-back has been found to be insufficient. In 2013 the Bow River saw extensive flooding with the flood return period

estimated at 80 years. This flooding resulted in several locations with lateral bank erosion greater than 100 meters (Yu et al., 2025). The 50-meter set-back also does not account for the rivers natural meander belt which ranges from 700-3000 m. The City faces the challenging task of balancing economic growth with public safety and environmental health. To support this effort, the city wants to further investigate the impacts of constricting a meandering river, with the goal of strengthening and potentially expanding their current set-back regulations.

1.3 Objectives

The goal of this research is to evaluate the effects of constricting the floodplain of a meandering river. To complete this, specific objectives include:

1. Develop a scaled version of a meandering river in a laboratory flume using alfalfa to simulate natural river conditions.
2. Introduce lateral floodplain constraints on the developed river to assess the impacts of constricting a meandering river.

Creating a meandering river within a laboratory setting has been done limitedly, a handful of previous studies have used cohesive material or vegetation to develop meandering rivers. This study aimed to create meanders that migrated laterally and downstream. To successfully create the conditions necessary for the river to develop, alfalfa was grown to provide bank strength. Following successful implementation of the first two objectives the river was then fully constricted on both riverbanks. This research is novel because it attempts to use rarely applied laboratory techniques to not only create a meandering river but also explore the rivers response to constrained conditions.

This research provides further insight into laboratory methods used to create a meandering river, it will highlight creating and maintaining room for rivers as a nature-based solution and be a stepping stone to help the city of Calgary expand and strengthen their set-back regulations.

1.4 Scope

The scope of this research includes completing three phases of flume experiments. This study was designed to focus on gravel-bed meandering rivers. While the flume experiments represent conditions similar to that of the Bow River, the results are intended to be broadly applicable to similar river systems. The experiments only cover an individual constriction scenario, representing a fully confined channel. A range of storm events including the 5-yr, 25-yr, 50-yr, and 100-yr storms are tested. The flume experiments are analyzed to assess changes in morphology and hydraulics; however, ecological and water quality aspects are beyond the scope of this study. The data collection is limited to aerial imagery and sediment transport measurements. The data is further analyzed using available software's such as MATLAB, Agisoft Photoscan Professional (Agisoft), and Microsoft Excel.

Chapter 2. Literature Review

This literature review outlines what a meandering river is and how they function, our current understanding on the effects of constricting a meandering river, why rivers need space to thrive, and outline previous laboratory studies where meandering rivers were created.

2.1 Meandering Rivers

Meandering channels are viewed as one of the most common forms of a river, as a result they have been extensively studied and are well understood (Howard, 2009). Figure 2 presents examples of meandering rivers from around the world.

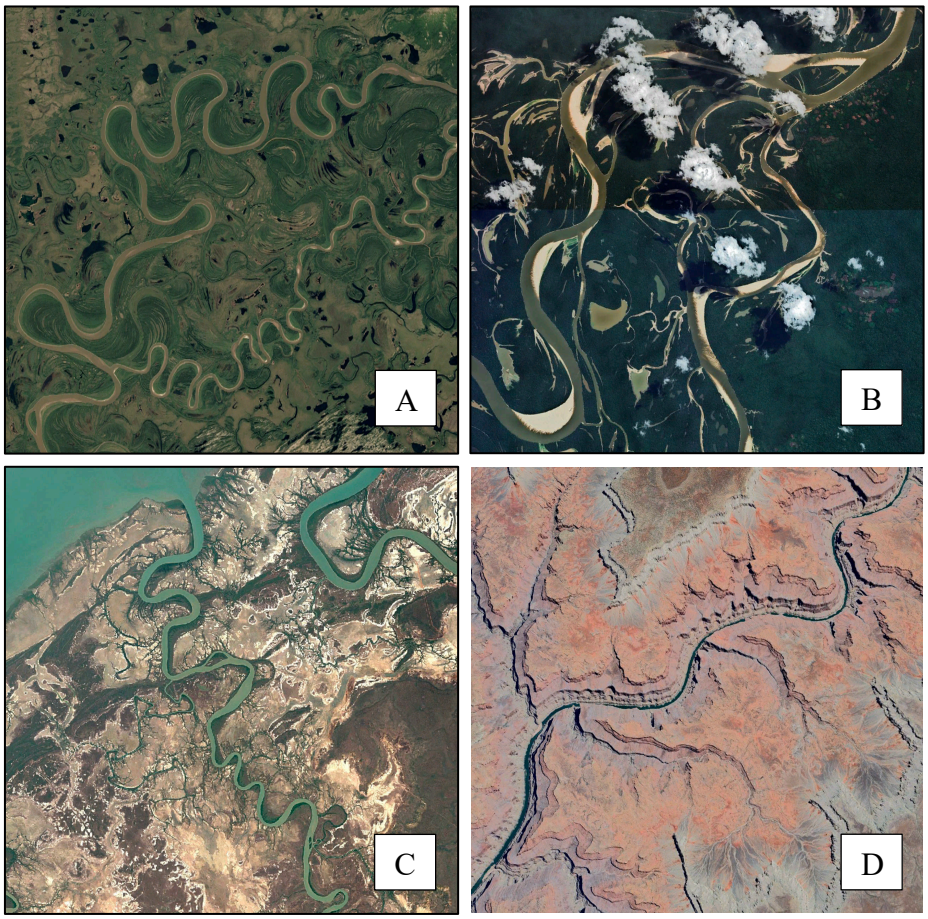


Figure 2. Meandering Rivers Around the World (a) Koyukuk River, Alaska USA (b) Jutaí River, Brazil (c) Bynoe River, Australia (d) Colorado River, Arizona USA *(*Google Earth Pro*, 2025)*

2.1.1 River Form

Meandering rivers are sinuous and predominantly single threaded. The dynamic nature of a meandering river results in lateral and downstream migration over time. Despite this, these rivers maintain consistent channel characteristics such as channel width, and radius of curvature (Kleinhans et al., 2024). The sinuosity of a river describes its planform geometry and is a ratio between channel length and valley length (Limaye et al., 2021; Snow, 1989). Typically, the sinuosity of a meandering river is greater than 1.5 (Leopold & Wolman, 1957; Wilzbach & Cummins, 2019). When a river's sinuosity is between 1-1.5 it is usually described as sinuous, and a river with a sinuosity of exactly 1 would be straight (Mueller, 1968). The meander wavelength is the distance between two successive inflection points of a meander, this distance is estimated to be between 7 to 10 times the channel width of the river (Leopold & Wolman, 1960). As meandering rivers are sinuous, they can be broken up into two sections, (i) the bends and (ii) the sections which connect the bends. Within the bends, deep pools develop along the outer bend while shallow bars form on the inner bends. These shallow bars are often referred to as point bars. In the sections that connect the riverbends, riffles are commonly found. Riffles are shallow areas within a river that typically have turbulent and fast-moving water (Leopold & Wolman, 1957). Figure 3 presents the characteristics of a meandering river.

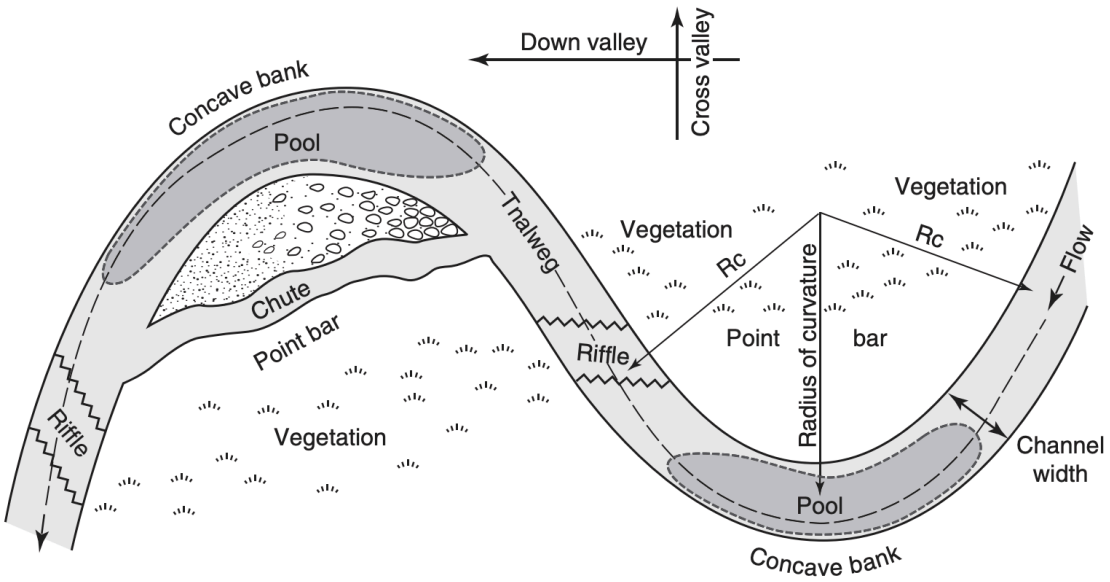


Figure 3. Meandering River Characteristics (J. M. Hooke, 2013)

2.1.2 River Dynamics

Bank erosion and bar deposition are two processes that help to create and maintain meandering within a river (Callander, 1978; Friedkin, 1945; J. M. Hooke, 2013; Kleinhans, 2010; Leopold & Wolman, 1960). Bank erosion occurs on the outside of a meander bend and bar deposition occurs on the inside of the bends. Through these erosive and depositional processes, a meandering river continuously changes throughout its floodplain. Whether meandering is driven by this bank erosion or bar deposition is an unresolved issue (Kleinhans et al., 2024). Nevertheless, another important river dynamic for meanders are avulsions. An avulsion is when a meandering river abandons a bend in the river through creation of a chute channel in the floodplain of a tortuous meander. Cut-off events like avulsions typically leave behind oxbow lakes but can also leave islands when an old channel is not abandoned. Bank erosion and bar deposition help to elongate meanders and increase sinuosity whereas cut-off events reduce sinuosity. Both processes are fundamental to the long-term evolution of a river's morphology (Callander, 1978; J. M. Hooke, 2013).

2.1.3 Factors Influencing Meandering Rivers

Although all meandering rivers share similar attributes, each meandering river has its own specific size, shape, and rate of evolution. A meandering rivers individual morphology is influenced by many factors including discharge, channel slope, sediment supply, riparian vegetation, and properties of floodplain soil (Zolezzi et al., 2012). Depending on the environment of a meandering river, each of these factors can hold differing significance to the river system. Discharge and sediment supply affect the morphology of a river as the river responds to the variations in water and sediment. These variations control the speed and quantity of erosion and deposition within the channel (Buffington & Montgomery, 1997; Church, 2006; J. Hooke, 2023; Schumm, 1985). Riparian vegetation and soil properties provide stability to floodplain and riverbank materials. This stability also referred to as bank strength, is a well-documented requirement for rivers to meander (Howard, 2009). Without significant bank-strength rivers become braided as water can easily erode multiple pathways. Riparian vegetation increases bank strength through root binding, increased deposition of fine cohesive sediments, and reduced channel velocities (Tal & Paola, 2010; Van Dijk et al., 2013). Soil properties provide varying levels of bank strength depending on the composition of the soils. Typically, a higher

content of clay and fine sediments results in increased bank strength. These varying bank strength properties affects the rate of erosion within the river channel.

2.1.4 River Resilience

River resilience from a geomorphic perspective is a rivers ability to recover toward the existing conditions that existed prior to the disturbance (Parsons & Thoms, 2018; Thoms et al., 2018). Resilience relates directly to dynamic stability, suggesting that a resilient river will experience changes but will ultimately maintain its functions and characteristics.

2.2 Riparian Zones

A riparian zone is the space found between a water course and the surrounding land. This zone has distinct hydrological gradients, soils, and habitats (Stutter et al., 2021). Riparian zones are widely acknowledged as biodiversity hotspots (Rohde et al., 2006; Stutter et al., 2021). These locations are also usually a transitional zone where natural processes meet anthropogenic processes (Stutter et al., 2021). Riparian zones and floodplains are closely related and commonly overlap. A floodplain refers to the land surrounding a river that periodically gets inundated. However, in urban environments where rivers are highly constricted and engineered, floodplains and riparian zones are often indistinguishable. Riparian zones are essential in creating a healthy river system. The complexity that helps create a flourishing ecosystem within a meandering river is due to the erosion and deposition that takes place within a river system (Amini et al., 2020; Garcia Lugo et al., 2015). These river processes cannot take place without sufficient riparian zones.

2.3 Floodplain Sedimentation

Sediments deposited within floodplains during high flow events are imperative for many ecosystem services and flood controls. Floodplain sedimentation fuels riparian zones by providing the nutrient rich soil required for riparian vegetation found alongside rivers in wetlands, fields, and forests (Opperman et al., 2017). In comparison to floodplains adjacent to inactive channels, active floodplains have significantly more total organic carbon (Thoms, 2003). The deposition of sediment shapes floodplains through sediment build-up. This deposition is commonly responsible for the creation of natural alluvial levees, and crevasse splays which increase floodplain heterogeneity and support a variety of ecosystems (Opperman et al., 2017).

2.4 Surface Water and Groundwater Interactions

Surface and ground water interactions within and around rivers are often referred to hyporheic exchange and occur within the hyporheic zone. Hyporheic exchange describes surface and shallow surface water mixing through porous river sediments. This exchange is responsible for hydrological, ecological, and biogeochemical interactions, and is driven by spatial and temporal variability in channel characteristics. Hyporheic exchange affects riverine ecosystems. Downwelling flow, which transfers solutes and surface water into sediment, influences the quality of subsurface habitats available for microorganisms and. Upwelling returns solutes to the river from the hyporheic environment, creating a source of nutrients for riparian ecosystems (Boulton et al., 2010; Tonina & Buffington, 2009).

2.5 Constraining Rivers

Many meandering rivers can be found in urban settings. Although rivers bring benefits to these locations, rivers also migrate, which can be a hazard for infrastructure and public safety. Because of this hazard, many rivers have been altered to remain in a fixed location. These anthropogenic constraints include construction of levees, embankments, bank stabilization, and channelization (Knox et al., 2022; Maaß et al., 2021; Nelson et al., 2024; Parsapour-Moghaddam & Rennie, 2018). In addition to rivers being anthropogenically constrained, rivers can also be found naturally constrained by river valley walls and bedrock outcrops (Parsapour-Moghaddam & Rennie, 2018; Rennie et al., 2018). Although it is known that providing room for rivers has many benefits, less is known on the morphological effects of constraining a meandering river (Amini et al., 2020; Garcia Lugo et al., 2015; Parsapour-Moghaddam & Rennie, 2018). Few papers have studied the effects of fully constrained river reaches, where flow is restricted on both sides along the entire length (Amini et al., 2020; Garcia Lugo et al., 2015). Garcia Lugo et al., (2015) completed experiments using physical modelling, Amini et al., (2020) completed research by employing a meander migration model, and Li et al., (2024) did a study evaluating the natural confinement of the Yellow River in China using remote sensing techniques. Both Garcia Lugo et al., (2015) and Amini et al., (2020) found that strong confinement produced regular planforms and low confinement allowed for more complex planforms to develop. These experiments suggested that small changes in constraint width can result in significant bedform and spatial variability (Amini et al., 2020; Garcia Lugo et al., 2015). Li et al., (2024) found that in

constrained sections of the Yellow River, the sinuosity was reduced and represented a transitional zone between straight and meandering. It was also found that the constrained sections had shorter wavelengths as the bends could not fully develop (B. Li et al., 2024). Parsapout-Moghaddem & Rennie (2018) studied a partially constrained river in Ottawa and found that a constrained river reach experiences greater bank instability, decreased sinuosity, and irregular meandering patters. Overall, these studies suggest that river morphology is highly sensitive to partial or complete constriction, and these constrictions tend to reduce sinuosity and restrict meander evolution.

2.6 Giving Rivers Space

It is widely known amongst fluvial geomorphologists and river engineers that a healthy meandering river is one that has the space it requires. Using room for rivers as nature-based solution has become more popular over the last few decades and has been described by many names throughout its time. These names include “room for the river”, “erodible corridor”, “fluvial territory”, “river corridor”, “freedom space”, “making room for the river”, “making space for water”, “meander belt”, and “riparian buffers” (Biron et al., 2014; McKergow et al., 2016; Nelson et al., 2024). Despite the lack of consensus on a name, there is common understanding that meandering rivers need room to thrive.

2.6.1 Functions of a Riparian Buffer

Riparian buffers have many benefits, including improved water quality (Arif et al., 2021; Drunpob & Chang, 2007; Han et al., 2023; Mundahl et al., 2023), erosion control, increased biodiversity, increased resilience, and flood protection (Klijn et al., 2018; Lee et al., 2004; Luke et al., 2019; McKergow et al., 2016; Nelson et al., 2024; Rohde et al., 2006).

A riparian buffer protects water quality by catching and filtering out sediment and debris from surface runoff prior to reaching the water course (Drunpob & Chang, 2007; Tomer et al., 2015). The sediment and debris carry nutrients which can be absorbed by the vegetation within riparian buffers. This interception of nutrients is important because excessive nutrient load can negatively affect water quality and cause things such as toxic algae blooms. The presence of vegetation within these buffers also increases the infiltration of the riparian soil. The increased soil infiltration then decreases the quantity of polluted water entering the river through surface runoff (McKergow et al., 2016; Tomer et al., 2015). Riparian buffers also provide shade through

vegetative cover, this cover helps maintain the required water temperatures for aquatic ecosystems to thrive (Luke et al., 2019).

Riparian buffers play an important role in maintaining and strengthening the biodiversity of riparian ecosystems. In general, the spatiotemporal complexity of riparian zones results in ecosystems that are species rich (Stutter et al., 2021). Vegetation within a riparian buffer is beneficial as it provides terrestrial ecosystems, cool water temperatures, and an essential source of carbon for stream food webs. Carbon is introduced to a river through falling wood and leaves. Fallen wood is also responsible for the creation of complex and varied habitats such as deep pools, and a place for fish to hide during extreme flood events (Luke et al., 2019; McKergow et al., 2016; Stutter et al., 2021).

Riparian vegetation protects the riparian zone from excessive erosion due to the added bank strength that vegetation root systems provide. The level of erosion control provided by vegetation depends on the density, vegetation type, and location (McKergow et al., 2016; Mundahl et al., 2023; Nelson et al., 2024; Stutter et al., 2021; Tomer et al., 2015). Vegetation also helps to capture fine sediments which increases cohesion in addition to reducing localised stream velocities by increasing drag. Overall, the added bank strength from vegetation provides erosion control against storm water runoff and stream channel discharges.

Rivers with access to sufficiently wide floodplains are more robust and resilient. When unconstrained, a river can shift within its floodplain, altering the relationship between discharge and flood levels. During high-flow events, the ability to spill into the adjacent floodplains helps to reduce river degradation by dissipating energy over a larger area. This lateral freedom allows a river to become less sensitive to uncertainties in discharge levels (Klijn et al., 2018). Restoring riparian buffer zones supports the restoration of wetlands and forested areas, both of which naturally dampen streamflow (Stutter et al., 2021). Ultimately, enhancing a rivers resilience through floodplain and riparian restoration can lower economic and human costs of flooding, while reducing the need for ongoing maintenance and structural improvements (Klijn et al., 2018).

2.6.2 Riparian Buffer Policies

Although fluvial geomorphologists and river engineers agree that rivers need room, there has been less of a consensus on the best way to implement that into society to inflict positive change

to river systems. There are two main ways that riparian buffers have been introduced, fixed and variable width solutions (Lee et al., 2004; Stutter et al., 2021). Fixed width solutions have a set width that do not change within the governed area. Fixed width solutions were likely introduced because of ease of implementation and very little spatial data requirements (Stutter et al., 2021). Variable width solutions consider other factors such as water quality, ecosystems, land use, etc. Once these variables have been taken into consideration they alter the buffer width accordingly. Width variability in buffers also requires immense quantities of data to properly implement and would require significant amounts of time and money. In 2004, Lee et al. undertook an extensive review on buffer policies in Canada and the United States. This study determined that in Canada and the United States mean buffer widths varied from 15.1m to 29.0m. Of these jurisdictions reviewed, only 44% of them had three or more modifying factors. Despite most guidelines within the United Stated and Canada using fixed width methods scientists believe we need to move toward more complex guidelines to control riparian zones (Lee et al., 2004; Luke et al., 2019).

2.6.3 Policy Implementation Issues

Implementing policies that involve providing a river with space has received a lot of push back over the last few decades. This pushback is due in part to the many industries that benefit from the riparian zones, such as land development, agriculture, and forestry (Hansen et al., 2015). In many growing urban areas, the land next to a river is highly sought after for development. In the forestry industry the buffers house valuable resources and within agriculture it provides space for further grazing or crop growth. Pushback is also a result of difficulty conveying hydrogeomorphic concepts, for example presenting bank erosion as a desirable river process (Biron et al., 2014). Erosion is seen by the public as a destructive process since it is highlighted by media during large flood events, and civil engineers have spent decades stabilizing banks. Policies are also difficult to implement because in dense urban areas many rivers have already been very closely surrounded by infrastructure that would be costly and time consuming to remove. Another aspect plaguing riparian restoration is the failure over the last few decades to report and document successes and failures of riparian management (Hansen et al., 2015). These restoration successes may be underreported because restoration responses may take years or decades to monitor and detect (Hansen et al., 2015). Simply put, rivers need more space but if documentation of successful restoration outcomes is not completed, then governing agencies will be less likely to implement those same successful management strategies.

2.7 Creating Meandering Rivers in a Laboratory Setting

Meandering rivers have been created in laboratory settings with ease; however, those studies tend to evolve into braided rivers as the meandering is unstable. Limited laboratory studies have created meandering rivers that are dynamic and stable. This paper reviews five key laboratory experiments undertaken to try and create stable meandering rivers. Amongst these experiments common methods included using cohesive sediments and vegetation. This review is grouped into three sections based on those categories, including cohesive sediments, vegetation, and upstream perturbation. Tables 1 and 2 summarize key conditions and characteristics of these five laboratory experiments.

Table 1. Summary of Laboratory Studies Flume Parameters

Study	Experiment Category	Flume Length (m)	Flume Width (m)	Flume Slope (-)	Channel D50 (mm)	Channel Width (cm)	Channel Depth (cm)	Sediment Feed Rate (kg/hr)
Smith (1998)	Cohesive sediment	3	1.2	0.015-0.025	N/A	N/A	N/A	N/A
Dulal & Shimizu (2010)	Cohesive sediment	1.8	0.9	0.008-0.02	N/A	4	3	N/A
Van Dijk, et.al. (2012)	Upstream Perturbation	11	6	0.0055	0.51	30	1.5	1
Tal & Paola (2007)	Vegetated	16	2	0.015	0.5	N/A	N/A	6.12-18.72
Braudrick, et.al. (2009)	Vegetated	17	6.1	0.0046	0.8	40	1.9	3-3.4

Table 2. Summary of Hydraulic and Morphologic Characteristics of Laboratory Studies

Study	Experiment Category	Discharge (L/s)	Froude Number (-)	Reynolds Number (-)	Wavelength (-)	Sinuosity (-)
Smith (1998)	Cohesive sediment	0.009-0.045	0.68-1.00	750-1750	3.75w	N/A
Dulal & Shimizu (2010)	Cohesive sediment	0.047-0.945	0.55-1.41	625-2300	3.33w-5.83w	N/A
Van Dijk, et.al. (2012)	Upstream Perturbation	1	0.58	3333	N/A	1.1-1.2

Tal & Paola (2007)	Vegetated	0.4-2.0	≈ 1	>3500	5w-11w	1-1.6
Braudrick, et.al. (2009)	Vegetated	1.8-2.7	0.55	4500	14w	1.19

2.7.1 Cohesive Sediment Experiments

Smith (1998) completed some of the first experiments where a meandering river was created in a laboratory. The objective of their study was to create well defined highly sinuous meanders in a flume. The experiments were completed in a 3 m long 1.2 m wide flume and used a variety of cohesive materials in attempts to create meanders. These materials included rock flour with kaolinite, corn-starch, cornstarch with calcined white China clay, diatomaceous earth (silica), and diatomaceous earth with calcined white China clay. For each experiment sediment was smoothed onto the flume and a straight initial channel was created. No sediment was fed into the flume throughout the experiment. In these experiments successful and well-defined meanders were created using three different cohesive sediment mixtures. Of the different mixtures tested a combination of diatomaceous earth and calcined white China clay was the most successful at creating meanders. Smith stated that the formation of point bars, erosion of the outer bank, and development of deeps and shallows were observed. The average wavelength of the meanders created were about 4 channel widths (Smith, 1998).

Dulal and Shimizu (2010) completed further cohesive sediment experiments. Their study was completed to address the issues relating to cohesion and its influence on river planform development. The experiment took place in a 1.8 m long, 0.9 m wide, and 0.25 m deep flume. Uniformly grained sand with a d_{50} of 0.11 m was used for a top layer and sediment with a d_{50} of 0.28 mm for the bottom layer. White Kaolinite was added to the top layer in different percentages to create cohesion and increase bank strength. The experiments used different combinations of sediment and thicknesses of each layer. The total thickness was always 5cm. These experiments took place over time periods ranging from 29 to 132 hours. The more successful experiments were continued for longer durations. The Dalul and Shimizu experiments produced a variety of results including meandering, braiding, and straight channels. They found that if too much clay is added to the top layer mixture the channel will be straight, and too little the channel will become braided. The most successful meanders were created with a 20% clay content in the top layer. These meanders exhibited erosion that behaved as slump block failure.

The meanders had wavelengths ranging from 3.3-5.8 channel widths. However, this experiment did not create pools and riffles (Dulal & Shimizu, 2010). Figure 4 displays pictures from both cohesive sediment experiments.

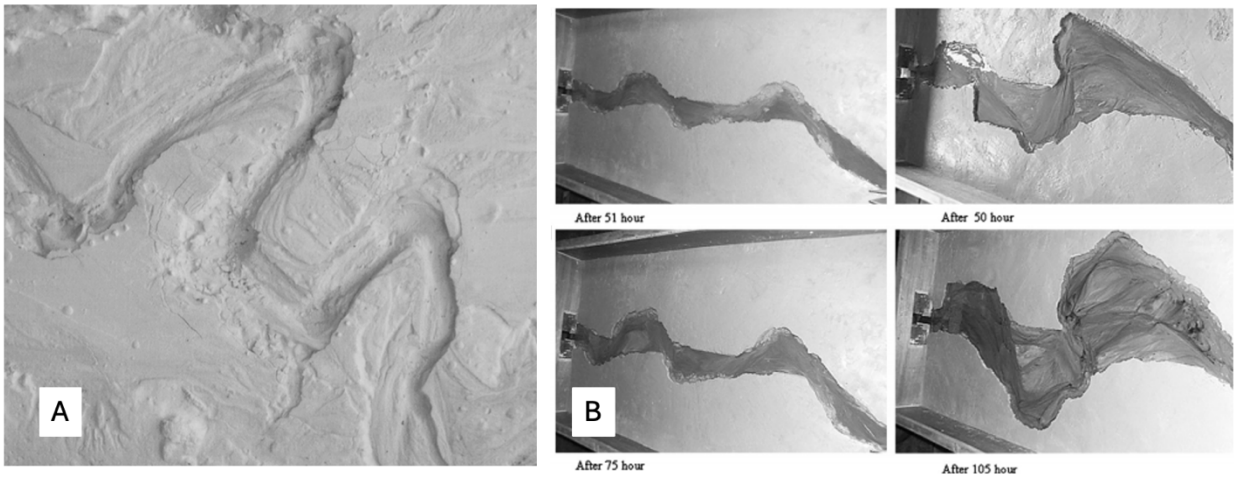


Figure 4. Cohesive Sediment Experiments (a) Experiment completed in 1998 by Smith; (b) A few experiments from the 2010 experiments completed by Dulal and Shimizu *(Dulal & Shimizu, 2010; Smith, 1998)*

Cohesive sediment experiments were overall successful at creating meanders in a laboratory setting. Some of the experiments even produced high sinuous meandering rivers (Smith, 1998). Different cohesive materials were successfully used including silica flour, calcined white China clay, diatomaceous earth (silica), and white kaolinite. These studies were able to produce general meandering structures and functions. These functions include bar formations, and bend erosion. Although these cohesive sediments were successful at creating meanders a main concern with the results are if these meanders represent natural rivers successfully. The first issue was that the cohesive sediments were not successful at creating cut-off events (Kodama et al., 2023). Secondly, as discussed in the 2010 paper by Dulal and Shimizu, cohesive sediments in the flume appeared to erode with slump block failure. Although slump block failure does occur in natural rivers, other types of erosion also occur. Rivers are significantly variable depending on the climate and landscape setting (Fryirs & Brierley, 2009) and the type of erosion that dominates in a river depends on the properties and state of the river. Therefore, slump erosion may be good at representing some rivers but not others. Additionally, the percent of cohesive sediment required to make the appropriate bank strength that results in a sinuous channel would lower the

representative grain size. This lowering of the representative grain size would make it harder to represent a coarse-grained river channel.

2.7.2 Vegetated Experiments

Tal and Paola (2007) undertook the first groundbreaking vegetative flume experiments. Their study looked at how bar and bank vegetation can influence a braided channel into a single-thread sinuous channel. The experiments used a 2 m wide 16 m long flume. The sediment used was a well sorted cohesionless sand with a d_{50} of 0.5 mm. Sediment was fed at a constant rate. This experiment started with a fully formed braided channel. This study used a two-stage hydrograph composed of a low flow period and high flow period for sediment transport. Sediment was fed into the channel. Alfalfa seeds were introduced during low-flow intervals of the braided channel experiments. The experiments took place over 119 and 138 days, and seeding was repeated during the experiments (Tal & Paola, 2007). This experiment resulted in successful meanders fluctuating between wandering and irregularly sinuous single threaded channels. Bar formation was observed throughout the experiments with vegetation even growing on the bars during low flow stages. The wavelength of the meanders created were found between 5-11 channel widths, however because the sinuosity was irregular it did not produce a characteristic wavelength (Tal & Paola, 2010).

Following the initial experiments completed by Tal and Paola, Braudrick et al., (2009) completed further experiments using vegetation. The motivation of Braudrick et al., (2009) experiments was to create not only a meandering channel but one that maintains channel migration once the sinuosity was developed. In the experiments a flume 6.1 m wide and 17 m long was used. The sediment utilized was sorted sand with a d_{50} of 0.8 mm. A channel was carved 40 cm-wide and 1.9 cm deep, it was generally straight, but an initial bend was placed at the inlet. Alfalfa was used to provide bank strength. The alfalfa took 7-10 days to grow and was reseeded every 15-20 h of run time. Sediment was also fed into the flume and consisted of a coarse and fine (lightweight plastic) sand. The experiment was completed over 136 hours. This experiment successfully created a meandering channel. The channel developed five bends and experienced five cut-off events. The channel width stabilized after the first 40 hours of the experiment, and the wavelength was determined to be approximately 14 channel widths with a sinuosity of about 1.19 (Braudrick et al., 2009). Figure 5 presents pictures from each vegetated experiment.

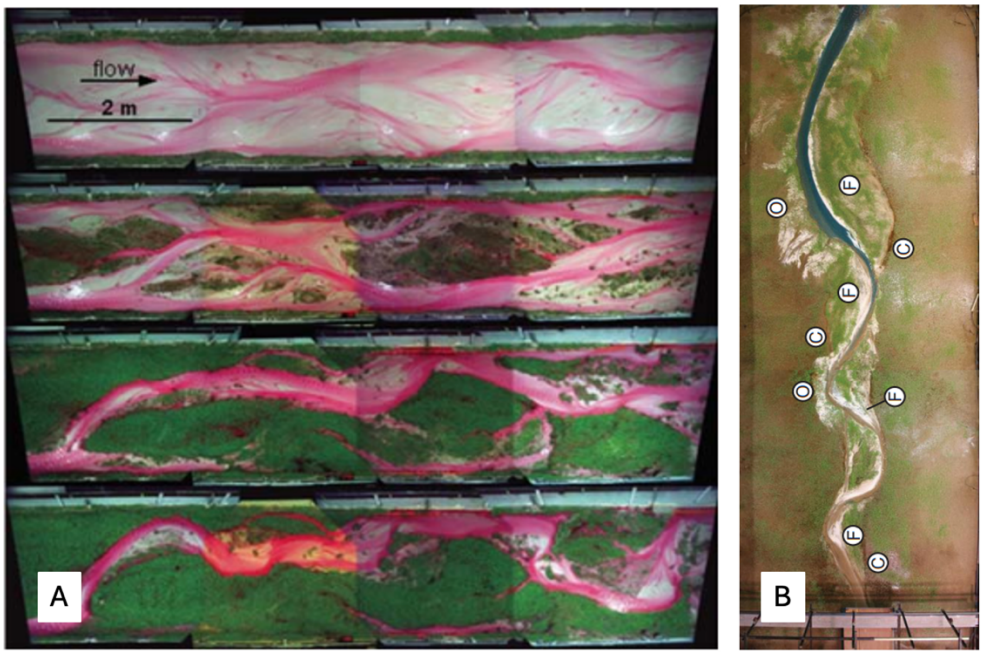


Figure 5. Vegetated Experiments (a) Tal and Paola (2007) experiments; (b) Braudrick et al., (2009) experiments

The vegetated experiments successfully exhibited bar formation, bend erosion, and cut-off events. This meant that not only did the meanders have functions and features of a natural meandering river, but the meanders successfully migrated across the floodplain. An important aspect with the Braudrick et.al, 2009 study was the addition of a non-cohesive lightweight plastic. The lightweight plastic acted as a fine sand. This method introduced an important way to combat scaling issues when trying to represent a coarse-grained river. There is no doubt that the vegetated experiments were successful. However, the addition of vegetation adds a complexity that needs to be accounted for. The density and type of vegetation used in experiments influences the rivers bank strength (Florsheim et al., 2008). One difference between the two vegetated experiments is the duration of the experiments. The Tal and Paola, 2007 experiment took place over 138 days, while the Braudrick et.al, 2009 experiment had a duration of 136 hours. While the Tal and Paola experiment took around 24x that of Braudrick's experiment, the migration exhibited by Tal and Paola was arguably less. Although this could be due to differences in discharge and sediment size, another factor is the density of the vegetation. From imagery analysis Tal and Paola's vegetation is much denser which may be a reason for the difference in migration.

2.7.3 Upstream Perturbation Experiment

Van Dijk et al., (2012) used a unique method of upstream perturbation in attempts to create a laboratory meandering river. This study sought to understand the necessary conditions for the formation of a dynamic meandering gravel bed river. The study was completed in a 11 m long 6 m wide flume. The sediment placed on the flume to a thickness of 10 cm was a poorly sorted sand with a d_{50} of 0.51 mm. The initial straight channel was carved out with dimensions 30 cm wide and 1.5 cm deep. A constant flow was used, and sediment was fed into the channel at the inlet. The sediment that was fed consisted of sand and silica flour mixed to a ratio of 4:1, the resulting d_{50} being 0.38 mm. Throughout the experiment the inlet where water discharged was moved left to right at a constant rate of 1 cm/hr. The experiments were completed over a 246-hour time period. The experiment resulted in the development of a low sinuosity meandering river that exhibited chute cutoff events and bend growth. A sinuosity of 1.12 was observed with a wavelength of about 3 m. However, how wavelength corresponded to channel width was not discussed by the authors (Van Dijk et al., 2012).

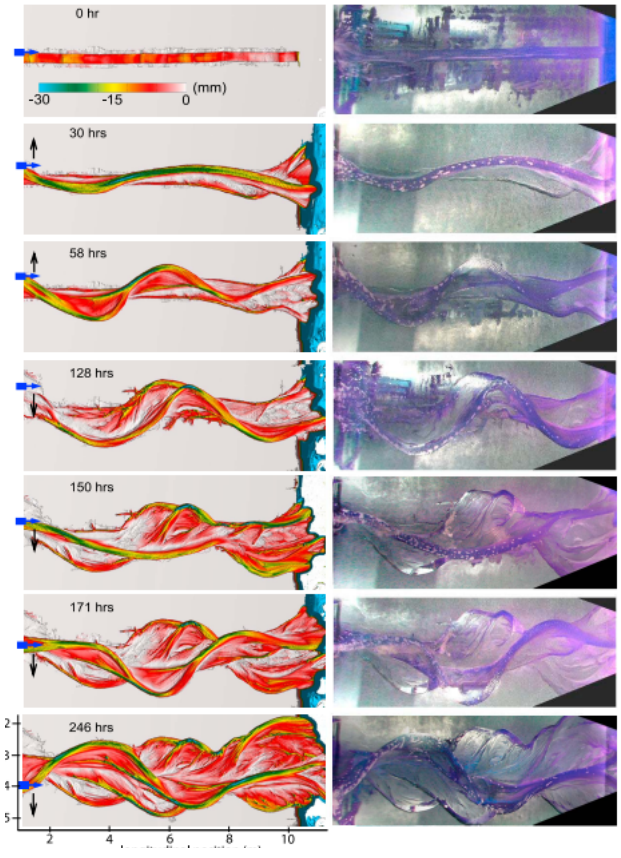


Figure 6. Upstream Perturbation Experiment (Van Dijk et al., 2012)

The experiments completed by Van Dijk et.al., 2012 were intriguing as they did not include cohesive sediment or vegetation. This is desirable because it avoids the complexities that the other methods add. The upstream perturbation accomplished by moving the channel inlet left to right created the instability in the river that allowed meanders to develop. Overall, the experiment was successful at creating meanders. The meanders exhibited bar formation, bend erosion, and cut-offs. The experiment was also able to represent a coarse-grained river. However, the key issue with this experiment was the rapid changes in the channel morphology. The meanders created using these methods resulted in many oxbow lakes being created. The water also did not consistently follow a single threaded channel. If the meanders were to change at any faster of a rate this experiment would have exhibited behaviors closer to that of a braided river. Even the authors stated that this 246-hour experiment represented 100-years of a river in France (Van Dijk et al., 2012). Due to the instability of the meanders created using this method it is unknown whether it is representative of a natural meandering river.

2.7.4 Summary of Laboratory Methodology Research Gaps

Research gaps exist in our understanding of the effects of constricting a meandering river developed within a flume. This is because key studies only focussed on creating stable meandering rivers, and laboratory research has not advanced towards the investigation of these rivers in response to differing conditions. Consequently, best ways to implement river constraints in a flume have not been established. While the key experiments were instrumental in developing successful methodologies, research gaps remain in understanding how to create a stable meandering river in a flume. One major gap from the two vegetated experiments, is information on the conditions necessary to replicate alfalfa growth within a flume. This includes gaps in information on duration of light, quality of light, saturation of soil, additional nutrients required, and density of seeding. Regarding the vegetation scale, it is unknown how the vegetation relates to the scale of a real-world river, and if the vegetation grown during each flume experiment best represents grasses, trees, or other plant types.

Chapter 3. Methodology

3.1 Overview

Flume experiments were completed on a mobile bed meandering river. These experiments involved three phases, including i) non-vegetated, ii) vegetated, and iii) vegetated and constricted experiments. All experiments were completed continuously, with the end of one experiment being the start of the next experiment. Figure 1 presents examples from each Phase of the flume experiments.



Figure 7. Phases of the flume experiments. (a) Phase 1 – Non-vegetated experiments; (b) Phase 2 – Vegetated experiments; (c) Phase 3 – Vegetated and constricted experiments

3.2 Flume Set-Up

The experiments were completed in the University of Waterloo's hydraulics lab. In the lab, there is a 2 m by 13.2 m flume where the experiments were conducted. As seen in Figure 8, the flume is equipped with a re-circulating water supply system, sediment collection baskets, a movable bridge, and a mobile camera cart. The flume is also equipped with an air compressor valve and an in-pipe flowmeter to control and measure discharge. To support vegetation growth while maintaining camera mobility, five adjustable grow lights were installed along the flume. Not depicted in Figure 8 is a 1-meter baffled chute, which allows for adjustment of the river inlet and the dissipation of energy. This chute is also referred to as the upstream perturbation system, because it can be shifted laterally during an experiment to move the waters entry location.

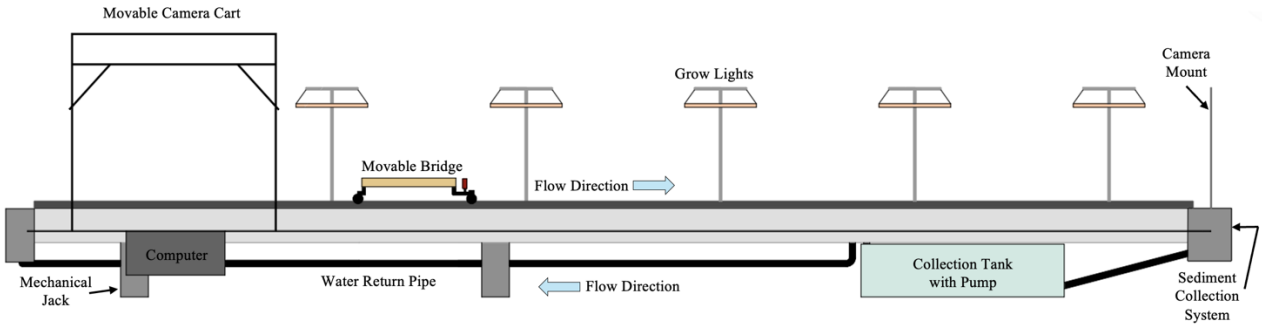


Figure 8. Flume Schematic

In preparation of the experiments, sediment was evenly distributed along the entire length of flume to an approximate depth of 5cm. The mean grain size (D_{50}) for the bed material was 0.76 mm, and the size distribution is presented in Figure 9.

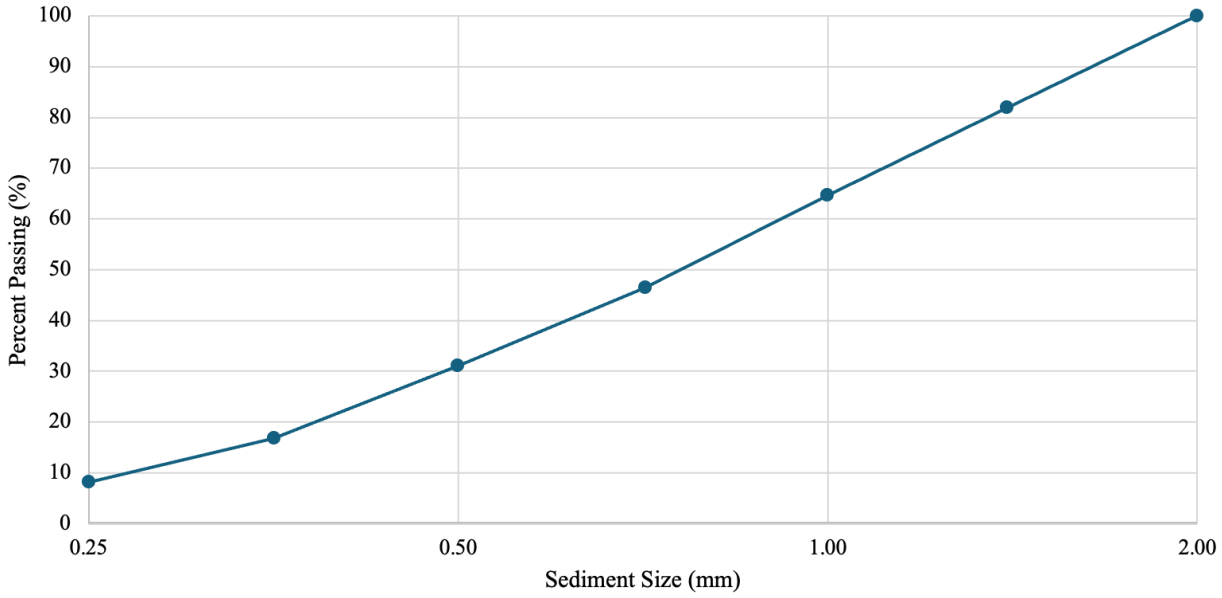


Figure 9. Feed and Bed Sediment Size Distribution

Once wetted, a straight channel 2 cm in depth and 20 cm in width was carved along the flume's centreline. To initiate meandering, a bend was also carved into the upstream end of the flume. This carved flow path extended 11 m along the flume's length. Upstream of the carved channel, the perturbation system, consisting of the baffled chute was placed on a 5 cm layer of sediment.

Unlike the bed material, this sediment had a different size distribution, generally ranging from 2 to 5.6mm in diameter. This larger sediment was placed with the expectation that it would remain stable and not be transported. At the interface between the chute and channel, large rocks were placed to ensure a smooth transition with minimal erosion. At the downstream end of the flume, a 3cm high lip was installed. This lip allowed sediment that was transported to be collected in the baskets while preventing accumulation at the end of the flume. Figure 10 presents the initial condition of the flume prior to the start of experiments.

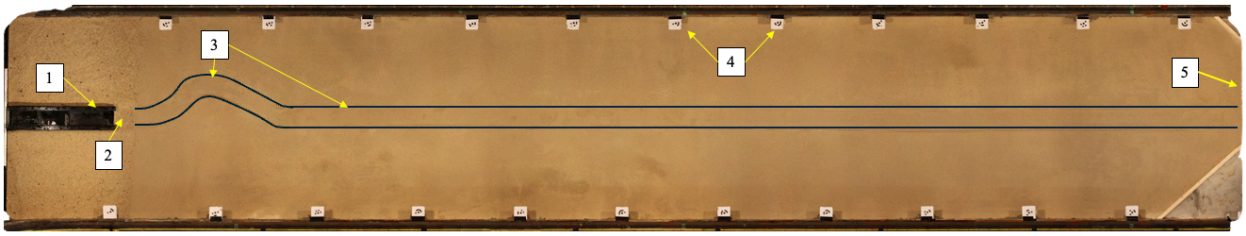


Figure 10. Initial Conditions Prior to Phase 1 Experiments. (1) Baffled chute; (2) Interface between chute and carved channel; (3) Carved bend and straight channel; (4) Targets; (5) 3cm lip

3.3 Scaling

To best represent the characteristics of the Bow River, it was decided to scale a real-world river to the flume. Unfortunately, the size of the Bow River was too large to scale to the labs flume. As a result, in conversation with the City of Calgary it was decided that a tributary of the Bow River would be used for scaling instead. Jumping Pound Creek, which meets the Bow River just 20 km northeast of the city extents was chosen as the tributary. This creek was chosen because of its similarities in attributes to the Bow River and the availability of data.

To reproduce the flow and sediment dynamics of Jumping Pound Creek at a reduced size, many parameters were evaluated using an iterative process to ensure an accurate scaled model. Turbulent flow (Re>2000) was required to promote river processes as it allows for the suspension of sediment. Subcritical flow was desired as most meandering rivers flow in subcritical conditions (Van Dijk et al., 2012). A Froude number equivalent to Jumping Pound Creeks Froude number was required. This method for scaling is referred to as Froude similitude as it ensures that the modelled conditions are the same as the real-world conditions (Julien, 2018). To create hydraulically rough conditions, the mean grain size (D_{50}) needed to be greater than 0.5mm (Kleinhans, 2010) and the particle Reynolds number needed to exceed 11.6 (Van

Dijk et al., 2012). When evaluating the flume's ability to transport sediment the Sheilds Diagram was referenced to ensure the incipient motion of the D_{50} was reached. Figure 11 presents the Shields diagram, along with the data point from the scaled model to illustrate the models incipient motion condition.

The iterative process, used to scale Jumping Pound Creek, began with choosing vertical and horizontal scaling factors. To determine these scaling factors many different scaling options were considered. Scaled lengths of the river model were calculated for each scaling option using the following formula developed by Julien (2018). x_r is the length scale, x_p is the real-world prototype length, and x_m is the flume model length.

$$x_r = \frac{x_p}{x_m}$$

Once all modelled flume lengths were determined hydraulic parameters was calculated by employing Froude similitude. With the Froude number of the modelled condition known, the velocity (V), Reynolds number (Re), Discharge (Q), particle Reynolds number (Re_*), shear stress (τ) and dimensionless shear stress (τ^*) could be calculated. The velocity (V) was calculated by rearranging the following formula, v is velocity in (m/s), g is the gravitational constant (m/s^2) and D_h is the hydraulic diameter (m).

$$Fr = \frac{V}{\sqrt{g * D_h}}$$

The Reynolds number (Re) was then calculated using the following formula. ρ is the fluid density (kg/m^3), and μ is the dynamic viscosity ($N*s/m^2$). This Reynolds number calculation uses the wide channel assumption which results in the hydraulic diameter being used as the characteristic length.

$$Re = \frac{\rho * V * D_h}{\mu}$$

The discharge was calculated using the following formula. A is the river channel area (m^2).

$$Q = V * A$$

The particle Reynolds number (Re_*) was calculated using the following formula. u^* is the shear velocity (m/s), D_{50} is the sediment diameter (m), and v is the kinematic viscosity (m^2/s).

$$Re^* = \frac{u^* * D_{50}}{v}$$

The following formula was used to calculate shear stress (τ). Where γ is the specific weight of water (N/m^3), R_h is the hydraulic radius (m), and S is the bed slope (m/m).

$$\tau = \gamma * R_h * S$$

Finally, the dimensionless shear stress ($\tau_b{}^*$) was calculated using the following formula. ρ_s and ρ are respectively the sediment and fluid densities (kg/m^3).

$$\tau_b{}^* = \frac{\tau}{D_{50} * (\rho_s - \rho) * g}$$

Following the calculations final horizontal and vertical scaling factors were chosen. The horizontal scaling factor was chosen as 1:100 and the vertical scaling factor as 1:50. These scaling factors were chosen as they satisfied all parameter requirements; maintaining specific hydraulic conditions, avoiding scaling issues, and remaining feasible within the flume. Figure 11 illustrates how the scaled conditions exceed the incipient motion threshold. . All data for Jumping pound creek was from the Kellerhals et al. (1972) report on the Hydraulic and Geomorphic Characteristics of Rivers in Alberta, or the data was generated using methods described in Appendix C.

Table 3 presents the final scaled parameters of Jumping pound creek. All data for Jumping pound creek was from the Kellerhals et al. (1972) report on the Hydraulic and Geomorphic Characteristics of Rivers in Alberta, or the data was generated using methods described in Appendix C.

Table 3. Scaling of Creek vs. Flume

Parameter	Units	Jumping Pound Creek	Scaled Flume
Vertical Scale	N/A	1	50
Horizontal Scale	N/A	1	100
Channel Width (T)	m	19.2	0.1920

Channel Depth (y)	m	1.07	0.0214
Froud Number (Fr)	-	0.3516	0.3516
Peak Discharge (Q)	m^3/s	23.4	0.0007
Sediment Size (D_{50})	m	0.03	0.0007
Velocity (V)	m/s	1.14	0.1611
slope (S)	m/m	0.0049	0.0049
Area (A)	m^2	20.54	0.0041
Hydraulic Diameter (D_h)	m	1.07	0.0214
Reynolds Number (Re)	-	1218750	3447
Particle Reynolds Number (Re*)	-	6804	23
Dimensionless Shear Stress ($\tau_b{}^*$)	-	0.0953	0.0719

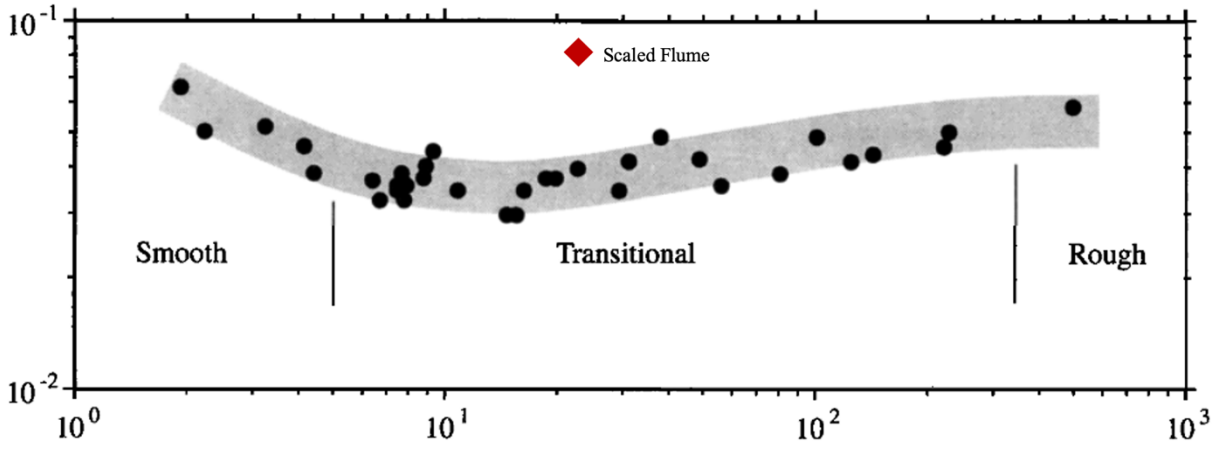


Figure 11. Scaled River Location on the Sheilds Diagram. *Buffington & Montgomery (1997)* redrafted from Rouse (1939) redrafted from Sheilds (1936)

3.4 Experimental Procedure

In total during the three phases, 35 experiments were completed between October and January of 2024. Five experiments were completed as non-vegetated runs, 24 were completed as vegetated runs, and 6 were completed as vegetated and constricted runs. A greater number of vegetated experiments were completed to allow the river to develop in attempts to create the best representative scenario. Each experiment consisted of a 6-hour hydrograph of varying storm sizes. These storm sizes included 5-yr, 25-yr, 50-yr, and 100-yr storms. Figure 12 presents the hydrographs used during these experiments.

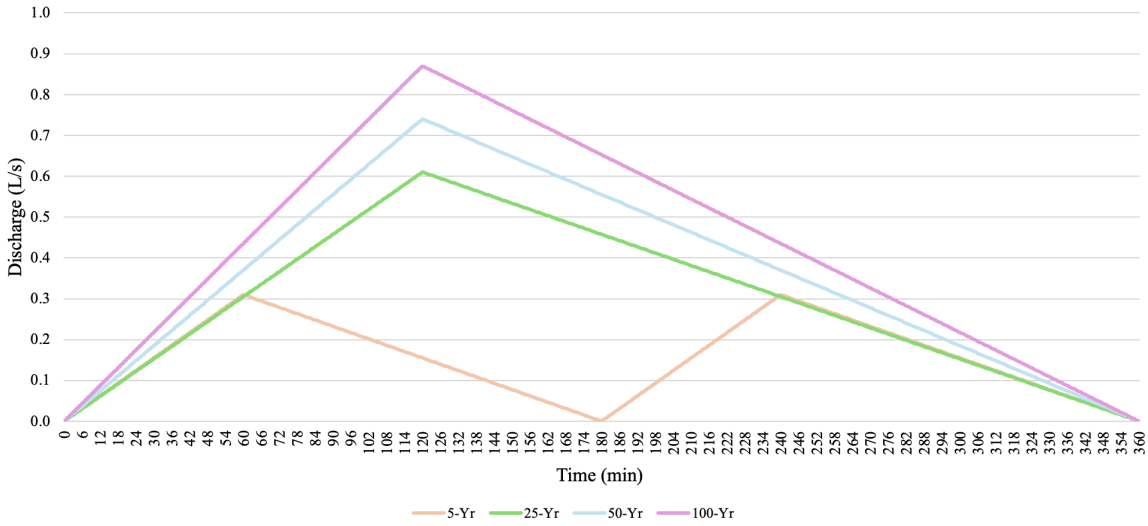


Figure 12. Experiment Hydrographs

The 25-yr, 50-yr, and 100-yr storms peaked after 120 minutes. The 5-yr storm experiment was an exception because it was a combination of two 5-yr storms resulting in two peaks over the experiment duration, with a peak at 60 minutes and a peak at 240 minutes. Although the valve was set to follow these hydrographs, its ability to control the discharge smoothly was limited, and resulted in larger stepped changes. The peak value for each storm was generated using methods seen in Appendix D.

Sediment fed into the river had the same size distribution as the bed material. Sediment was fed manually at the top of the flume every 10 minutes during flows that produced sediment transport. The sediment input quantities for each storm were calculated to match the estimated sediment output quantities. These quantities were calculated using the following Meyer-Peter & Müller (1948) equation which estimates sediment transport.

$$q_b = A_m * (\tau_b{}^* - \tau_c{}^*) * \sqrt{g * R} * D_{50}{}^{1.5}$$

Where q_b is the volumetric rate of sediment transport ($m^3/s/m$), A_m = 3.97 and represents the an empirical coefficient determined by Wong & Parker (2006), $\tau_b{}^*$ is the dimensionless shear stress (-), $\tau_c{}^*$ and is the critical shear stress (-), g is the gravitational constant (m/s^2), R is the relative density (-), and D_{50} (-) is the mean sediment diameter. From these calculations, the 5-yr storm did not result in significant sediment transport and as such no sediment was added during those

events. The total sediment input for the 25-yr, 50-yr, and 100-yr storms were 1472 g, 4567 g, and 6369 g respectively. Table 4 outlines the sediment input for each storm.

Table 4. Experiment Sediment Input Schedule

Time (mins)	Dry Sediment Input (g)		
	25-yr	50-yr	100-yr
0-50	0	0	0
60	0	7.32	4.02
70	1.46	44.89	41.59
80	17.09	110.33	126.42
90	47.15	187.66	231.96
100	89.28	277.94	359.58
110	138.43	390.78	515.77
120	195.57	514.67	689.91
130	212.19	537.8	781.23
140	177.94	478.62	728.05
150	153.41	422.24	636.74
160	130.52	357.53	550.17
170	101.75	306.15	456.25
180	75.5	258.02	368.42
190	57.33	203.75	296.52
200	41.45	161.59	230.77
210	22.95	123.47	162.4
220	8.77	88.3	102.69
230	1.47	58.09	58.09
240	0.01	27.83	24.53
250	0	8.77	4.02
260	0	1.46	0
270-360	0	0	0

The upstream perturbation system was moved 1-cm every hour for the first fourteen experiments completed. This was done to represent the planimetric perturbation that a natural channel would exhibit (Van Dijk et al., 2012). After the fourteen experiments this method was removed from the experimental procedure as it was resulting in sediment build-up at the top end of the flume.

For all vegetated experiments, the grow lights were set to a schedule where the lights would turn on for 12 hours starting at 7pm and then turn off at 7am. This allowed experiments to run during the daytime. Before each vegetated experiment the grow lights would be adjusted so they were

out of the way for the experiment and data collection. Figure 13 presents the two different grow light configurations.



Figure 13. Adjustable Grow Lights (a) Grow lights over top of flume; (b) Grow lights adjusted to the side of flume

3.5 Phase 1

Throughout the non-vegetated experiments water was run through the initial flume set-up at the specified storm sizes. The channel morphology was allowed to develop without interference. All applicable procedures discussed in Section 3.4 were followed. Table 5 presents details of the non-vegetated experiments.

Table 5. Phase 1 Experiments

Experiment	Date of Experiment	Storm Size
LMR_Exp1	October 8th, 2024	5-yr (1/2 experiment)
LMR_Exp2	October 8th, 2024	5-yr (1/2 experiment)
LMR_Exp3	October 9th, 2024	25-yr
LMR_Exp4	October 10th, 2024	50-yr
LMR_Exp5	October 11th, 2024	100-yr

Originally, the 5-yr storms were split into two different experiments, 3 h each. However, because the experiments were run on the same day and could not dry in between, this was later changed

because any pictures taken between the two experiments had too much glare. Hence, the first two storm sizes in Table 5 indicate ½ experiment.

3.6 Phase 2

3.6.1 Growing the Alfalfa

During the last non-vegetated experiment from Phase 1, while the water was still running the flume was seeded. Seeding during an experiment was imperative to limit alfalfa growth within the channel. Any seeds that fell into the channel were washed downstream and collected into the sediment baskets. To seed the channel consistently, the flume was subdivided into 1-meter length sections. In each one-meter section, 60 g of alfalfa seeds were spread using a hand sieve onto the bed sediment. Additional seeds were added to any sparse areas as needed. The alfalfa was then left to grow for 10 days; this allowed the alfalfa to germinate and develop roots. The alfalfa was watered 2-3 times a day, for the first three days while the alfalfa germinated. While the seeds were germinating, they were not exposed to light. This was because it was determined in previous experiments that light was not advantageous for alfalfa germination. Following the germination the alfalfa was exposed to 12-hrs of light from grow lights every day. Any alfalfa that grew directly within the channel was removed. The flume was only re-seeded once, following germination in locations where limited germination occurred.

3.6.2 Preliminary Vegetated Experiments

During the preliminary vegetated experiments, 5 storm events were completed. These events also followed the procedures in Section 3.4. Table 6 outlines the details of the preliminary vegetated experiments.

Table 6. Phase 2 Preliminary Experiments

Experiment	Date of Experiment	Storm Size
LMR_Exp6	October 22nd, 2024	5-yr (1/2 experiment)
LMR_Exp7	October 22nd, 2024	5-yr (1/2 experiment)
LMR_Exp8	October 23rd, 2024	25-yr
LMR_Exp9	October 24th, 2024	50-yr
LMR_Exp10	October 25th, 2024	100-yr

3.6.3 Vegetated Experiments

Following the last preliminary vegetated experiment (LMR_exp10) one main issue was identified and rectified prior to continuing the remaining vegetated experiments. Large sediment located upstream of the channel became dislodged and entered the main channel; this was causing sediment build-up within the first meter of the modelled river. To rectify this issue, it was decided to stop the upstream perturbation of 1cm/hr during the experiments. The larger sediment surrounding the baffled chute was removed and replaced with the bed material. Additionally, two bricks were placed following the chute to better direct the sediment into the channel. Lastly, the larger sediment that had entered the channel was removed. Figure 14, presents this location before and after the changes.

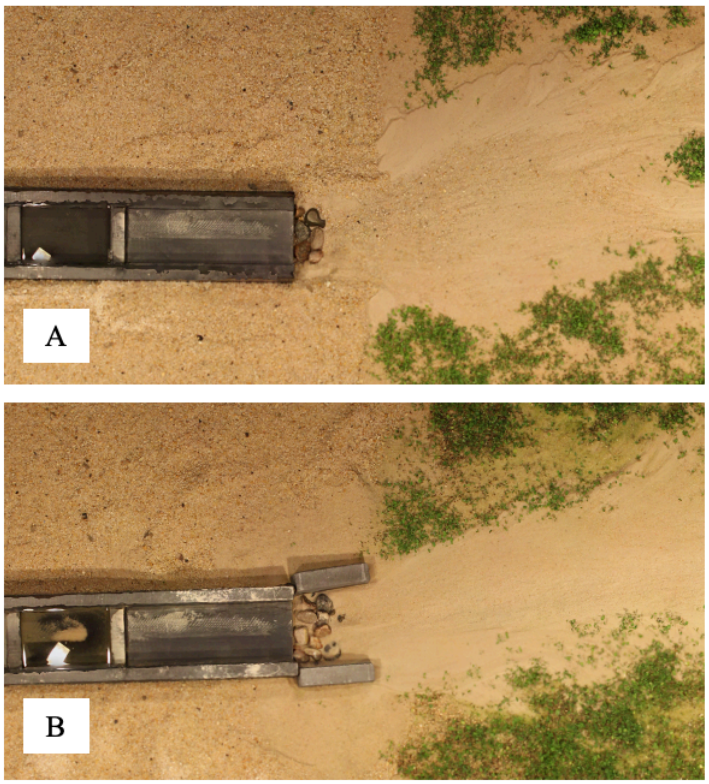


Figure 14. Upstream Boundary Configuration Adjustments (a) boundary configuration prior to adjustments; (b) post adjustment boundary configuration

In addition to addressing the boundary condition issues, the decision was made to remove the 5-yr and 50-yr storm scenarios. Instead, the focus shifted to the 25-yr and 100-yr storms, aiming to promote bar deposition during the 25-yr event and bank erosion during the 100-yr event.

Following these changes, nineteen additional vegetated experiments were completed. Table 7 outlines the details of these vegetated experiments.

Table 7. Phase 2 Experiments

Experiment	Date of Experiment	Storm Size
LMR_Exp11	November 4th, 2024	5-yr
LMR_Exp12	November 5th, 2024	25-yr
LMR_Exp13	November 6th, 2024	50-yr
LMR_Exp14	November 7th, 2024	100-yr
LMR_Exp15	November 11th, 2024	100-yr
LMR_Exp16	November 12th, 2024	100-yr
LMR_Exp17	November 13th, 2024	25-yr
LMR_Exp18	November 14th, 2024	25-yr
LMR_Exp19	November 18th, 2024	100-yr
LMR_Exp20	November 19th, 2024	100-yr
LMR_Exp21	November 20th, 2024	25-yr
LMR_Exp22	November 21st, 2024	25-yr
LMR_Exp23	November 25th, 2024	100-yr
LMR_Exp24	November 26th, 2024	100-yr
LMR_Exp25	November 27th, 2024	25-yr
LMR_Exp26	November 28th, 2024	25-yr
LMR_Exp27	December 2nd, 2024	100-yr
LMR_Exp28	December 3rd, 2024	100-yr
LMR_Exp29	December 4th, 2024	100-yr

3.7 Phase 3

To constrict the channel following the vegetated experiments flexible PVC sheets were hammered into the sediment. These PVC sheets were 10 cm in height and were hammered to the bottom of the flume. The sheets were placed approximately 25 cm from the edge of the riverbank and roughly followed the curvature of the river bends. This constriction configuration was chosen to represent the type of constriction seen along the Bow River in Calgary. The scaled length of 25 cm corresponds to 25 m. This length was chosen for two reasons: first, to illustrate a

case scenario worse than the current regulation of 50 meters. However, jumping pound creek is much smaller than the Bow River, as a result this is only a moderate constriction. Secondly, the length was chosen to avoid changing the morphology of the river when the constrictions were being hammered into the sediment. Putting the constrictions too close could alter the river bank locations. Details of the vegetated and constricted experiments can be seen in Table 8.

Table 8. Phase 3 Experiments

Experiment	Date of Experiment	Storm Size
LMR_Exp30	December 10th, 2024	100-yr
LMR_Exp31	December 11th, 2024	25-yr
LMR_Exp32	December 12th, 2024	25-yr
LMR_Exp33	December 16th, 2024	100-yr
LMR_Exp34	December 17th, 2024	100-yr
LMR_Exp35	December 18th, 2024	25-yr

3.8 Data Collection

3.8.1 Aerial Imagery & Timelapse

Before and after each experimental run, photos were taken of the existing flume conditions. To limit reflections, the aerial images were taken the following morning after all the surface water had drained from the bed and the sediment was given time to dry. Photos were taken at two different camera angles using two Canon EOS Rebel T5i cameras, with a fixed focal length of 20mm and a sensor resolution of 5184 × 3456 pixels. This method followed that of the one set-up by Peirce et al. (2021). These photos were taken every 0.25 m starting from the upstream end and moving towards the downstream end of the flume.

In addition to the aerial photos, a stationary camera located at the downstream end of the flume captured one picture every 5 minutes during each experiment. The camera was set to a height which allowed the full width of the flume to be visible in every image.

3.8.2 Sediment Collection

The sediment collection baskets at the downstream end of the flume were meshed-lined and allowed sediment and debris to be collected as the water flowed through. The baskets were emptied following the end of the rising limb and the end of the falling limb for each storm event.

Each sediment sample was stored in its own clear container and allowed to completely air dry. In addition to the sediment, the baskets also collected any vegetation and debris that was transported out of the flume.

3.9 Data Processing & Analysis

3.9.1 Organics Error Testing

Prior to processing of sediment, three samples were chosen to determine the influence of organic matter on the sediment masses. To conduct these tests, three representative samples were tested. These samples included high, medium, and low organic content. This was determined visually, with the low content sample having minimal organic matter, the medium having some organic matter, and the high content with significant organic matter. The organic contents of the samples are presented in Figure 15.

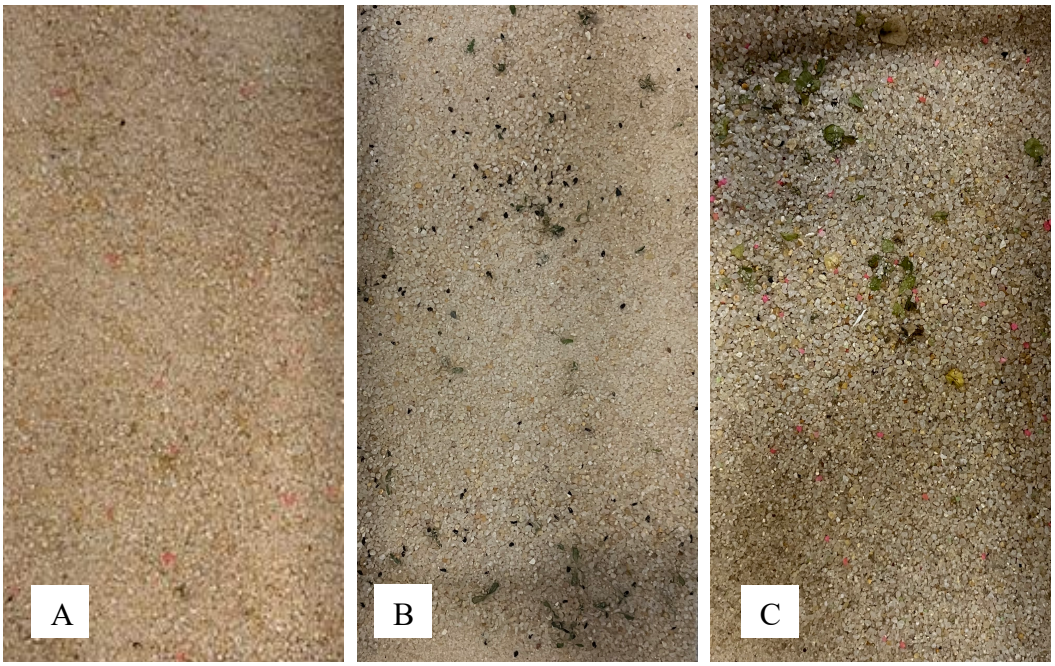


Figure 15. Organic Content of Representative Sediment Samples (a) low organic content (b) medium organic content (c) high organic content

These samples were tested following ASTM D2974 guidelines with a few modifications, this guideline outlines the standard test methods for determining moisture, ash content, and organic material of soils (ASTM Standard D2974-20e1, 2020). The purpose of the test was to determine the organic masses in each representative sample. The three samples were air dried, weighed, and then placed into a 550^{o}C furnace. The samples remained in the furnace for 3.25 hours until they

were completely ashed. The recommended temperature to do this is 750ºC however the furnace used did not support that temperature. The samples were then removed and placed in in a sealed desiccator to cool to room temperature. Once cooled, the samples were weighed. The mass of the dried samples could then be compared to the masses after placed in the furnace. The mass error of the three samples ranged from 0.14% to 0.17%. Which determined that the organic content found within all sediment samples was insignificant.

3.9.2 Sediment Processing

The first step in processing the sediment collected for each storms rising and falling limb was to weigh the samples. Once each sample was weighed, they were sieved. To sieve the samples a screen shaker was used. Screen shakers use vertical vibration to sieve sediments through screen trays. The screen tray sizes that were used are as follows, 1.41mm (No.14), 1.00mm (No.18), 0.71mm (No.25), 0.5mm (No.35), 0.35mm (No.45), and 0.25mm (No.60). Approximately half of each sample collected was sieved, once sieved the sediment collected on each screen tray was weighed and recorded.

3.9.3 Topographic Analysis

To obtain the aerial imagery required for topographic analysis, twenty-three targets were installed along the outer edge of the flume. These targets were spaced one meter apart on both sides of the flume, this resulted in a target every 0.5 meters. The targets overhung the flume as they were positioned 20-30 cm above the flume bed. Prior to the first vegetated experiment an additional ten targets were added to the flume to improve imagery analysis results.

The images taken by the two Canon cameras were stitched together using the application Agisoft. Using the targets installed within the flume, Agisoft processed the overlapping images to generate 3D data, resulting in both stitched photo mosaics and digital elevation models (DEMs) of the flume surface. The vertical accuracy of the successful DEMs taken after the addition of extra targets was estimated at 2.04 mm $\pm$ 0.2 mm based on a comparison of the DEMs and surveyed control point elevations. The DEMs were then analyzed in MATLAB using custom scripts. Before analysis the DEMs created in Agisoft were detrended to correct for the flumes tilt. From the corrected surfaces, difference of DEMs (DoDs) were created to highlight areas of deposition and erosion between specified experiments. These DoDs and DEMs were then further analyzed by applying masks to isolate and examine specific areas within the flume.

Chapter 4. Results

This section of the report describes the river generation of all three phases of the experiments. The results include digital elevation model differencing, descriptions of river morphology, sediment transport, streamflow dynamics, and biological features.

4.1 Topographic Analysis

As outlined in the methodology section, for each experiment, aerial photos were run through Agisoft to create a stitched photo mosaic of the entire flume. Once run through the software, a summary report was produced that quantified the uncertainty in each experiments photo mosaic, as summarized in Table 9. The benchmark used to determine successful imagery processing was if the vertical error was less than 3 mm. Due to limitations with the first four experiments, a vertical error of less than 7 mm was the successful benchmark. Following experiment 4, additional targets were introduced to improve imagery results, which is why the vertical error benchmark was reduced. Based on the 3 mm and 7 mm error criterion, 14 experiments imagery was successfully processed. With the lower threshold for non-vegetated experiments, all of them were successfully processed. Most of the vegetated experiments had errors that exceeded the 3mm benchmark by more than an order of magnitude, this result suggests a breakdown within the methodology. The growth of the vegetation seemingly leads to problems with imagery collection. Of the successful experiments, the average vertical error was 6.41mm for the first four experiments and 2.05mm for the remaining successful results. For each successful experiment Agisoft created a stitched photomosaic and a DEM. Examples of each can be seen in Figure 16 and Figure 17.

Table 9. Agisoft Photoscan Error Results

Experiment	X error (mm)	Y error (mm)	Z error (mm)	Successful (Y/N)
LMR_exp0	6.26	3.78	6.46	Yes
LMR_exp1	5.83	3.23	6.62	Yes
LMR_exp2	6.46	3.2	6.38	Yes
LMR_exp3	6.52	3.31	6.53	Yes
LMR_exp4	6.11	3.48	6.05	Yes
LMR_exp5	3.78	3.45	1.92	Yes
LMR_exp6	Nonsensical	Nonsensical	Nonsensical	No
LMR_exp7	Nonsensical	Nonsensical	Nonsensical	No
LMR_exp8	3.78	3.4	1.83	Yes
LMR_exp9	3.79	3.42	1.89	Yes
LMR_exp10	3.77	3.36	2.02	Yes
LMR_exp11	605	191	115	No
LMR_exp12	3065	1912	1463	No
LMR_exp13	Nonsensical	Nonsensical	Nonsensical	No
LMR_exp14	275	311	612	No
LMR_exp15	1349	624	824	No
LMR_exp16	2573	769	356	No
LMR_exp17	3.74	3.43	1.97	Yes
LMR_exp18	3.75	3.42	2.06	Yes
LMR_exp19	260	281	516	No
LMR_exp20	203	304	617	No
LMR_exp21	437	500	820	No
LMR_exp22	9.44	22.7	75.4	No
LMR_exp23	19.01	10.38	5.65	No
LMR_exp24	8.65	8.21	30.34	No
LMR_exp25	3.74	3.39	2.52	Yes
LMR_exp26	6.37	10	43	No
LMR_exp27	23.64	48.71	51.1	No
LMR_exp28	9.22	14.25	39.93	No
LMR_exp29	19.35	29.4	73.02	No
LMR_exp30	6.06	5.98	36.9	No
LMR_exp31	6.65	7.29	3.067	No
LMR_exp32	5.18	5.31	29.82	No
LMR_exp33	3.73	3.4	2.16	Yes
LMR_exp34	6.28	5.87	30.3	No
LMR_exp35	3.73	3.36	2.1	Yes

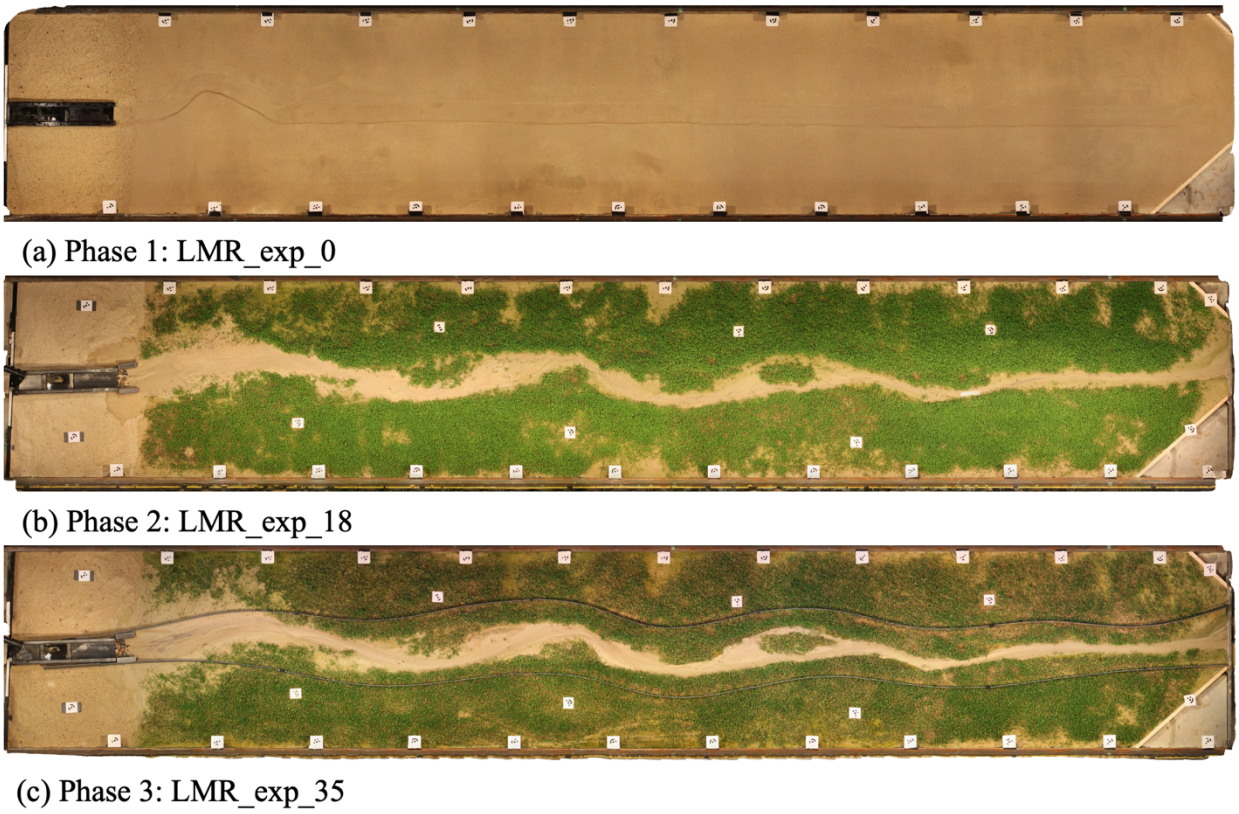


Figure 16. Examples of Stitched Photo Mosaics

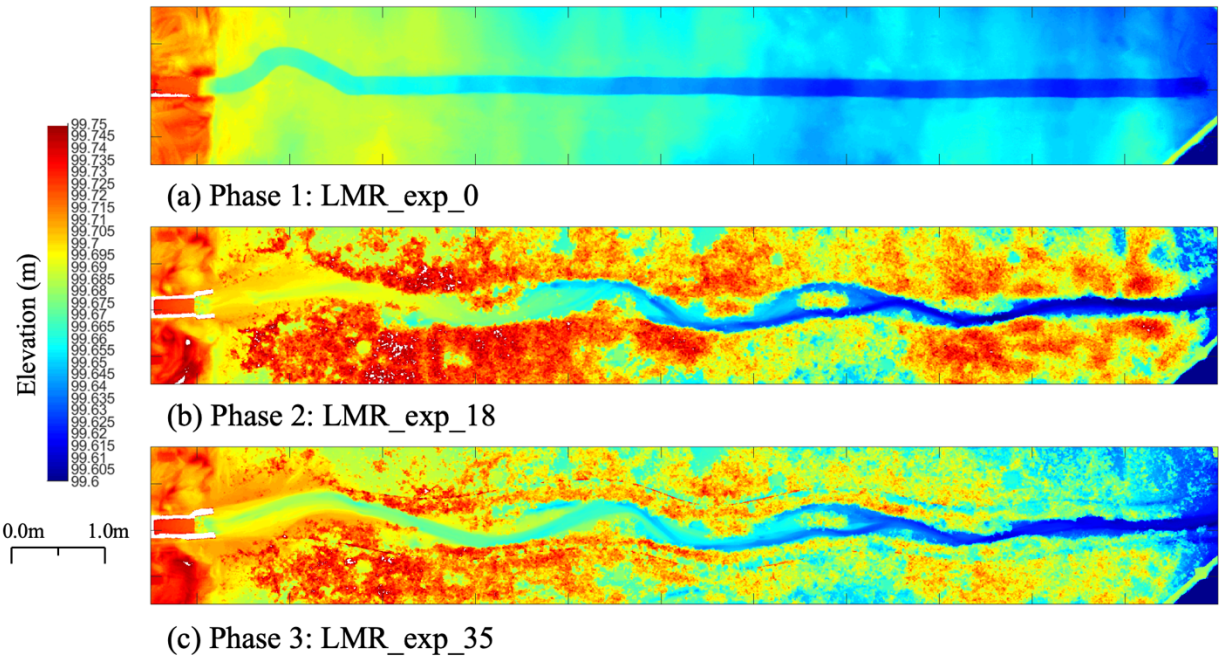


Figure 17. Examples of Digital Elevation Models

Using MATLAB digital elevation model differencing was performed between each successful experiments DEM. The resulting DoDs illustrate how the rivers morphology evolved during each phase of the study. These models highlight areas of erosion and deposition; red areas indicate erosion while blue indicate deposition. The intensity of each colour corresponds to the magnitude of change, deeper reds or blues represents greater change. These DoDs tell the story of how the river developed and migrated throughout time. Identifying these morphological changes, especially following the introduction of constrictions, is essential for understanding the impact of constricting the floodplain of a meandering river. Please note that all the DoDs presented in sections 4.1.1-4.1.3 are masked, excluding the floodplains so changes within the active channel can be clearly presented.

4.1.1 Phase 1 DoDs

During phase 1 for which the initial channel was straight with only one pre-existing bend, the river experienced significant morphological development driven by natural fluvial processes. During these first five experiments bends were eroded, and bars were deposited. In total seven bends were developed accompanied by the formation of six distinct bars and one island. The sediment deposition was not limited to bar formation as deposition was observed along the entire length of the initially carved channel. The first bend experienced the most significant morphological changes throughout the five experiments as it expanded laterally. This expansion was likely driven by the shifting position of the upstream perturbation system which changed the rivers flow path and ultimately initiated downstream bend migration. A summary of all DoDs during phase 1 is presented in Figure 18.

4.1.2 Phase 2 DoDs

Two important observations were made when assessing the Phase 2 DoDs. First, once the Alfalfa was introduced, the meander generation became limited. The meanders appeared to freeze in place and most changes were found only within the channel instead of throughout the floodplains and channel. The second observation was the significant deposition in the first four meters of the river and erosion in the remaining seven meters. This upstream deposition and downstream erosion suggest that the river was not in equilibrium as the sediment was getting stuck in the upstream end of the river. Figure 19 presents the DoDs between each successful experiment in Phase 2.

4.1.3 Phase 3 DoDs

The Phase 3 DoDs revealed a contrasting story to that of the Phase 2 river development; presented in Figure 20. Instead of upstream deposition and downstream erosion, Phase 3 was characterized by upstream erosion and downstream deposition. The introduction of channel constrictions reduced the width, consequently increasing the channel velocity. This increased velocity resulted in a large erosion event in the upstream portion of the river flushing out the sediment that was deposited during Phase 2. The eroded sediment was subsequently deposited in the sediment starved downstream reaches. Nearing the end of Phase 3, erosion was occurring along the entire river length, leading to river entrenchment. Along riverbanks, deposition within the floodplains were observed, however it was difficult to distinguish these areas in the DoDs as the alfalfa located within floodplains produced issues with the data.

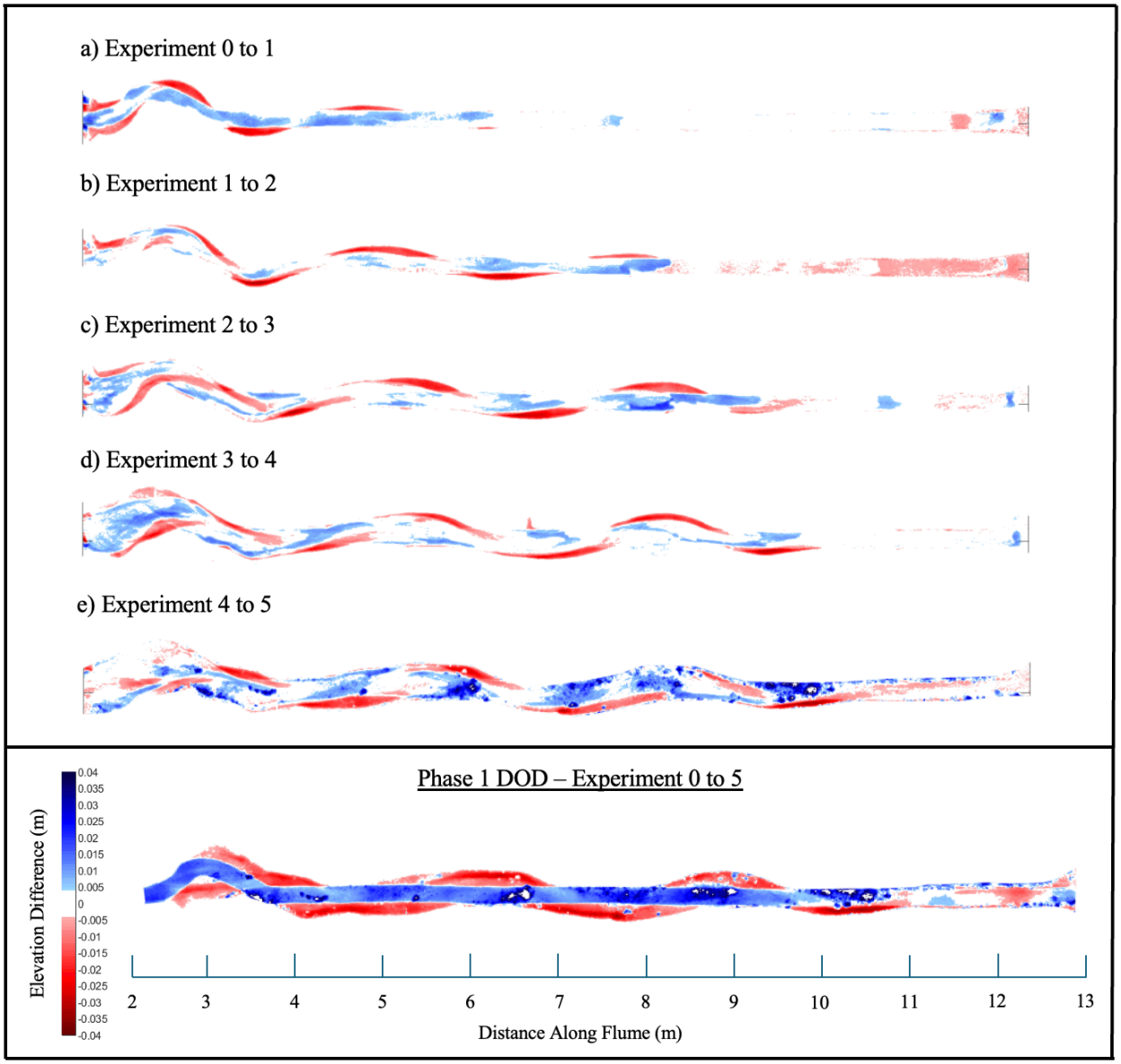


Figure 18. Phase 1 DoDs

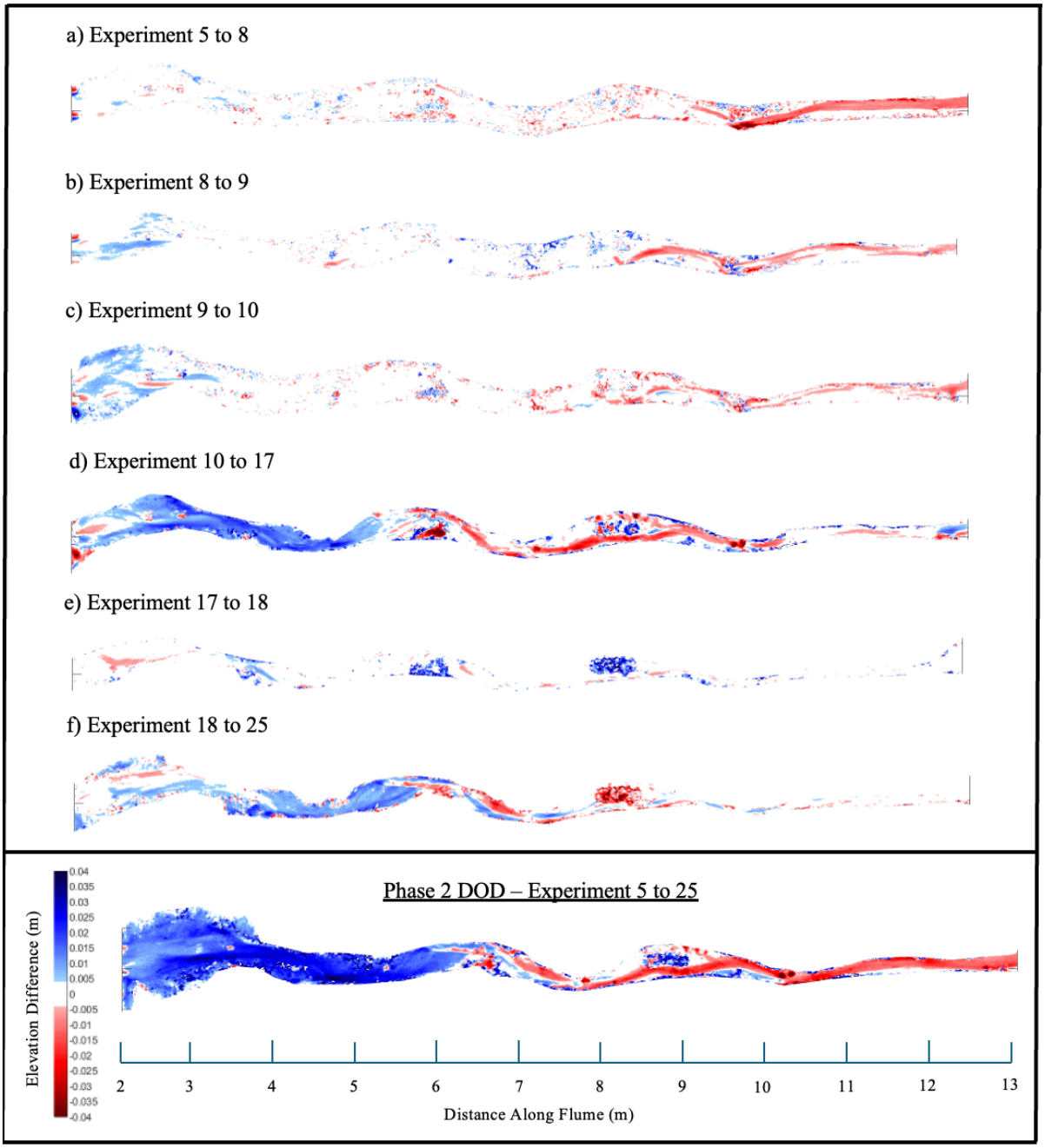


Figure 19. Phase 2 DoDs

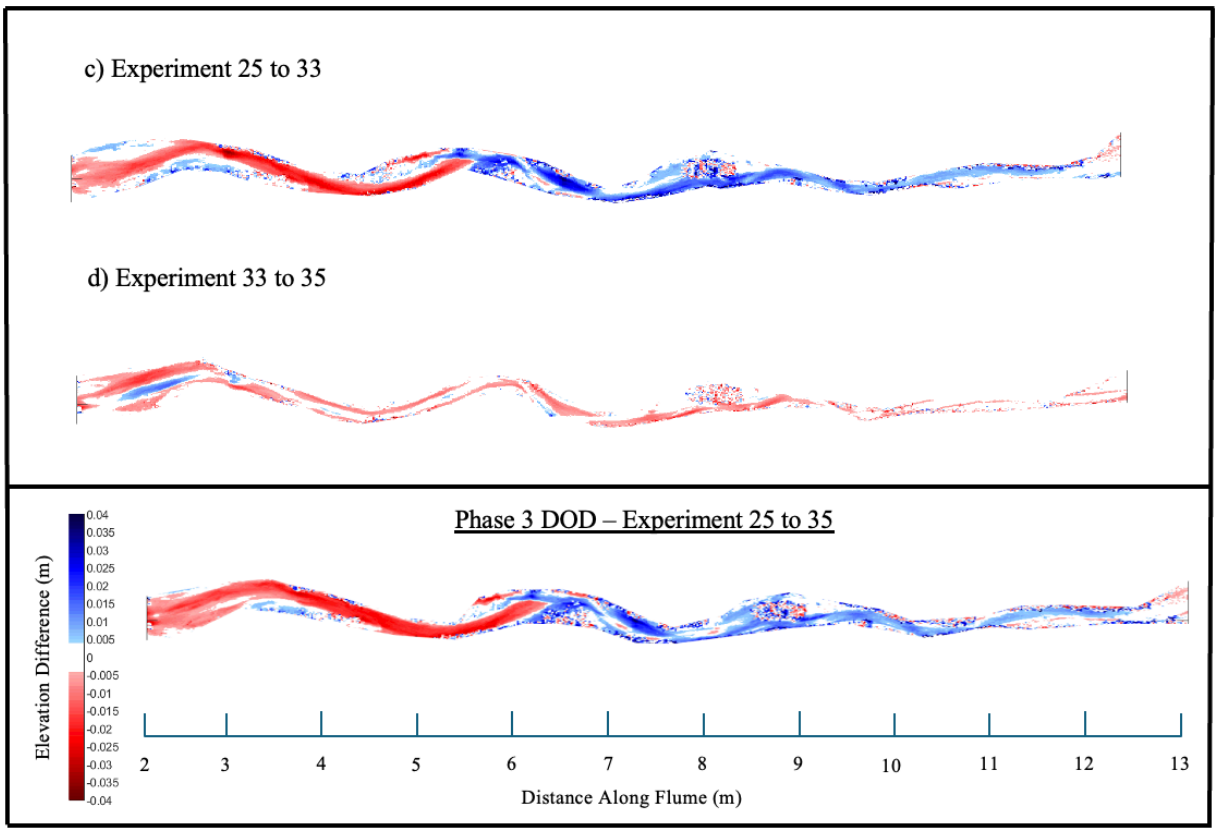


Figure 20. Phase 3 DoDs

4.2 Morphology

The general morphology of the living meandering river was evaluated after each experimental phase was completed. This evaluation was completed on the final experiment in each phase that produced successful topographic imagery results. For Phase 1, 2, and 3 the representative experiments were LMR_exp5, LMR_exp25, and LMR_exp35 respectively. Table 10 presents the morphology following each experiment phase and the morphology of jumping pound creek for comparison.

Table 10. Summary of General Morphology

Parameter	Phase 1: LMR_exp5	Phase 2: LMR_exp25	Phase 3: LMR_exp35	Jumping Pound Creek (scaled)
Sinuosity (-)	1.037	1.043	1.046	1.67
Channel Width (m)	0.168	0.144	0.122	0.192
Meander Wavelength (m)	2.54	2.43	2.59	N/A

The sinuosity, channel width, and meander wavelengths were measured using the stitched mosaic photographs in an AutoCAD software. Overall, when comparing the flume's river to Jumping Pound Creek the morphology was less sinuous and had a reduced width. The meander wavelength could not be compared, as jumping pound creeks meander wavelengths were extremely variable and one number would not be an accurate description. As discussed in section 4.1, once Alfalfa was introduced meander evolution was limited. This is further supported as very minimal morphological changes were noticed between each experimental phase. The general shape of the river stayed consistent, maintaining the initial 7 bends developed during Phase 1. The sinuosity and wavelength between each experiment differed slightly. This minimal difference is a result of small changes within the river, specifically at the upstream most bend. The most significant morphological difference observed between each phase was the average channel width. The average width between Phase 1 and 2 was reduced by 2.4cm and 2.2cm between Phase 2 and 3. The reduction in width between the first two phases was due to the erosion in the downstream end which caused the channel width to be narrowed. This width reduction was continued into Phase 3 expanding further upstream once the constrictions were

introduced. To better illustrate the changes in general morphology, Figure 21 presents the approximate bank full flow path for all three experimental Phases.

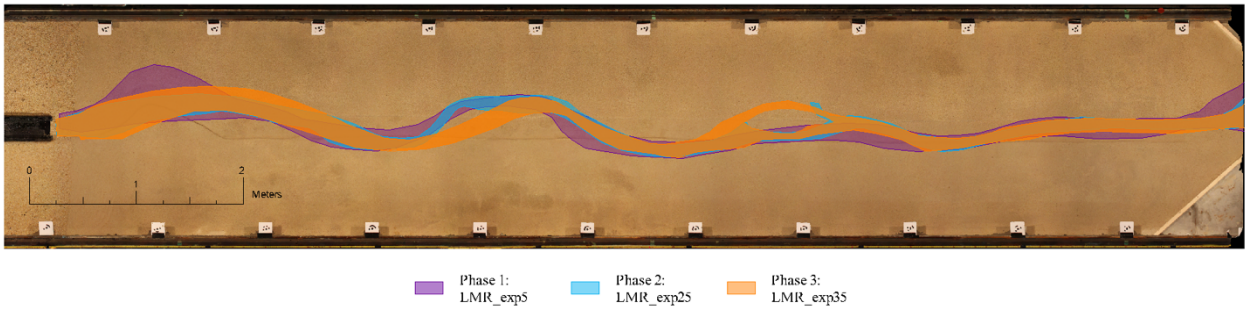


Figure 21. Bank Full Flow Paths

Figure 21 also highlights key morphological features not discussed when evaluating the general morphology. During Phase 2, flow within the floodplain increased due to the deposition in the upstream end blocking flow paths. This floodplain flow returned to the main channel by eroding a small gully on the left bank of the river just after the island. In phase 3 this gully was inactive, however, flow around the left side of the island resumed.

To identify locations of pools and riffles, and how they changed across experimental phases, a profile of each phase's thalweg was plotted (Figure 22). Pools were identified as any sudden elevation changes equal or greater than 0.01m. In Phase 1, seven pools were identified, this correctly corresponds to the number of bends, as pools typically form along the outsides of bends in meandering rivers. For Phase 2, interestingly seven pools were also observed. However, these pools were in different locations than the pools from Phase 1. Three pools in the upstream end were filled, and an additional three pools formed at the downstream end. This signifies increased complexities of the development within the channel. Phase 3 also had seven pools identified, as the pools from Phase 2 persisted. The pools appeared to be shifted downstream, likely a result of the constrictions significant effect on sediment export. The three pools in the upstream section from Phase 1 appeared to be re-forming during Phase 3, however they were not significantly large enough to identify as pools based on the 0.01m criteria.

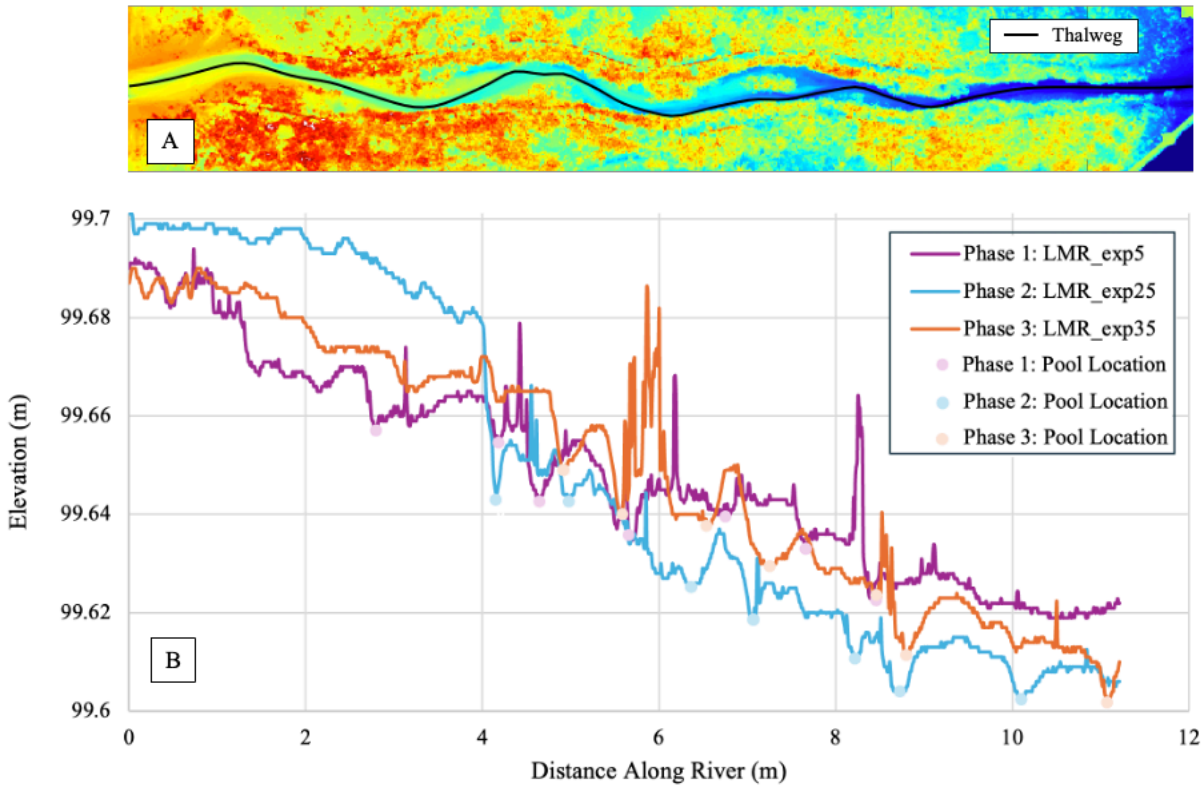


Figure 22. Thalweg Plan and Profiles from Phases 1-3 (a) Plan view of profile plotted on the DEM from LMR_exp35; (b) Thalweg Profiles with pool locations identified

The thalweg profiles not only identify pools and riffles but also illustrate patterns of sediment deposition and erosion over time. These profiles support the results discussed in section 4.1, clearly showing that Phase 2 experienced significant upstream sediment deposition within the first four meters of the river, and erosion in the downstream seven meters. Figure 23 highlights the transition zone between upstream deposition and downstream erosion, located approximately 4 m along the flume. Just beyond this transition, the channel narrows significantly. This section, referred to as the pinch point, may have induced a backwater effect, promoting sediment deposition upstream. However, when the constrictions were added the flow and velocity increased and were strong enough to carry sediment past the narrow section.

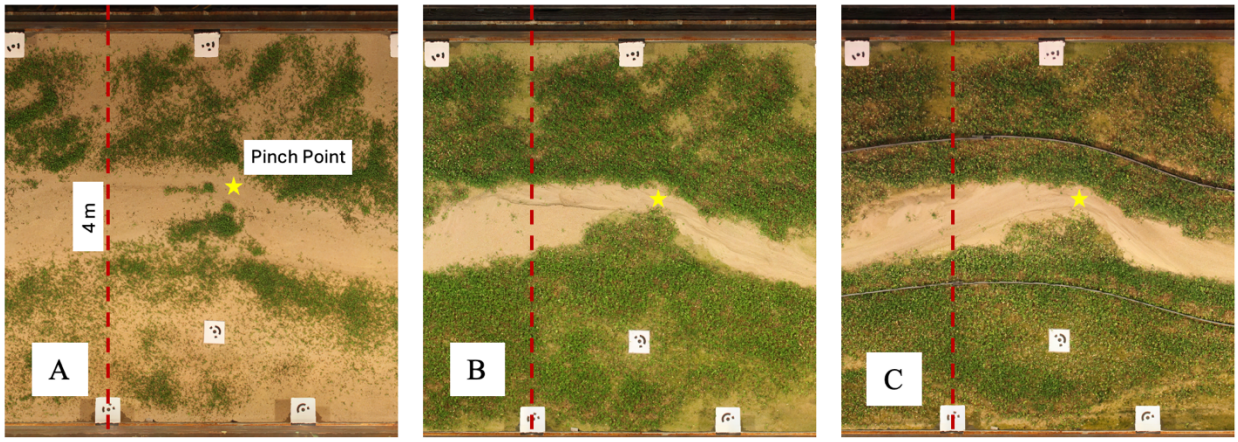


Figure 23. Transition point of upstream deposition to downstream erosion (a) LMR_exp5; (b) LMR_exp25; (c) LMR_exp35

4.3 Streamflow Dynamics

The flow introduced to the channel was consistent between all three phases of the study as it was controlled by a valve and dictated by set hydrographs. Although the quantity of water input into the flume was consistent, the flow paths and hydraulic features within the flume were variable.

4.3.1 Phase 1 Streamflow

During Phase 1 as the river was being developed the flow was isolated to the channel. The floodplains were noticeably wet appearing to be fully saturated with water. In a few low-lying areas where the initial bed material depth was less than 5cm, there were puddles where the water table elevation exceeded the floodplain elevation. Flow depth throughout this Phase remained consistent, but deeper in the pools along the outer meander bends. During the final experiment of Phase 1 (LMR_exp5) an additional flow path developed, creating an island within the channel (Figure 24).

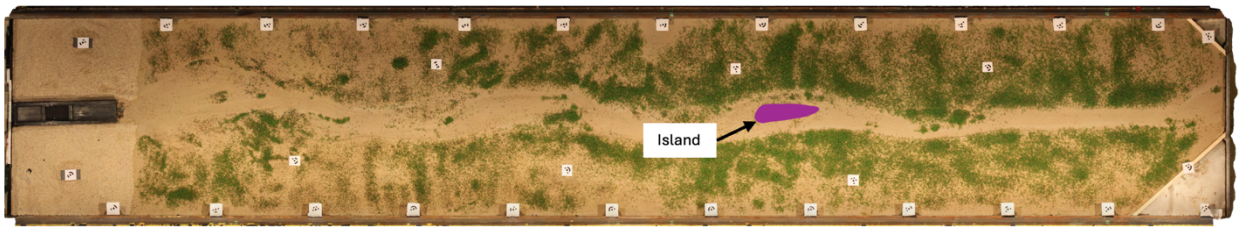


Figure 24. Island Developed during LMR_exp5

4.3.2 Phase 2 Streamflow

More extensive streamflow dynamic observations occurred during Phase 2, as it was significantly longer than Phase 1. Hydraulic jumps were intermittently observed directly downstream of the river inlet. These hydraulic jumps formed when substantial sediment deposition occurred, increasing the slope and producing supercritical conditions. At the interface between the supercritical and subcritical flows, hydraulic jumps formed. As these hydraulic jumps are concentrated locations of turbulence and energy dissipation, rapid erosion of the underlying sediment took place. As sediment was scoured the hydraulic jump would migrate upstream until the slope was reduced and subcritical flow conditions were re-established. The flow depth of Phase 2 was shallower in the upstream end due to the sediment deposition, and deeper in the downstream end where erosion had entrenched the river and reduced the flow width. As with Phase 1, the pools that were not filled in with sediment had greater flow depths. The flow during Phase 2 was predominately within the active channel for experiments 6 through 24, however flow around the left side of the island was never present. Following experiment 24 enough sediment had built up within the first four meters of the river to completely block off the main channel. As a result, the rivers flow was diverted through the floodplains. Despite the diverted flow a chute channel was not created within the river as the alfalfa provided enough bank strength to limit erosion. Although no chute was formed, as mentioned in section 4.2, a gully was eroded where the water re-entered the main channel. The sediment block remained until the constrictions were added. Due to the flow entering the floodplain the water level within the floodplain was visually higher and remained fully saturated along the entire flume until the straight section of the river, where the water table was lower than the floodplain. Figure 25 presents the sediment blockage and location of the gully formed during Phase 2.



Figure 25. Sediment Blockage and Gully Location

4.3.3 Phase 3 Streamflow

Throughout Phase 3 due to the constrictions, flow was re-directed back through the main channel and minimal flow entered the floodplains. Since the constrictions were not sealed to the bottom of the flume water was still able to enter the floodplains past the constrictions. However, from visual observations, the water table decreased significantly, and the soil was not visibly saturated. Water was observed hitting the PVC sheets, suggesting that the water depth within the active channel was significantly increased in comparison to that of the first two phases. This was likely a result of the lower water table within the floodplains. Because of the water level increase, flow along the left path of the island resumed.

4.4 Sediment Transport & Export Dynamics

4.4.1 Sediment Transport

Each phase of the experiment saw differing sediment transport results. Figure 26 presents the total mass output from the flume for each experiment.

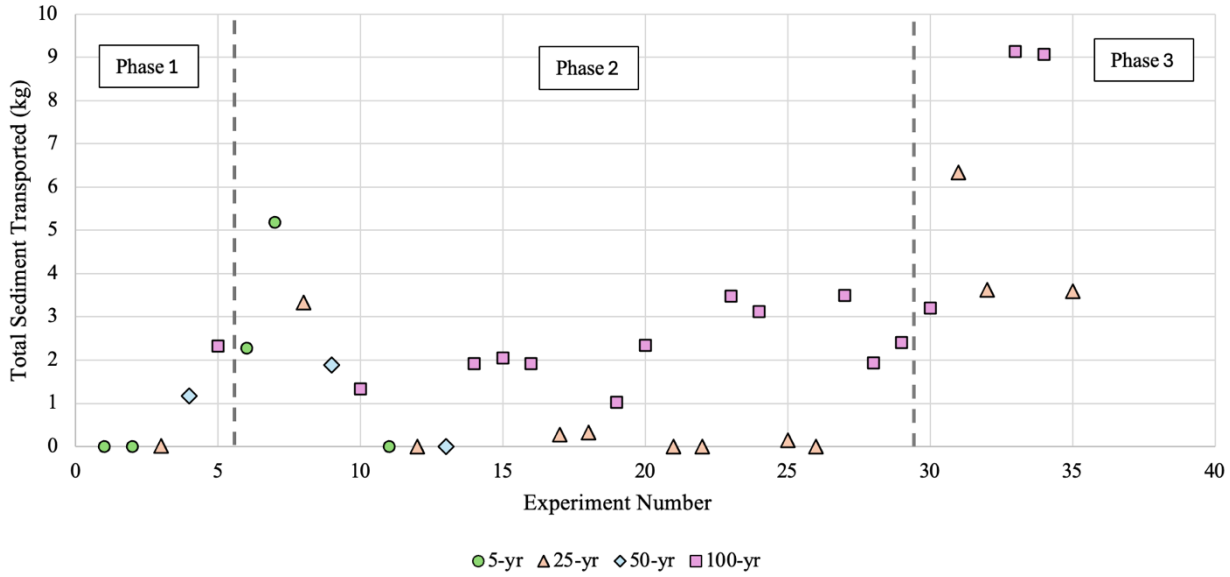


Figure 26. Total Mass Output of Experiments

During Phase 1, there was initially no sediment transport collected because the transported sediment was redeposited within the channel, on bars, and in the floodplain. A distinct sediment surge, also referred to as a gravel sheet, was observed slowly migrating downstream. This gravel sheet transported sediment through avalanching along the flume bed. By the fourth experiment, the surge reached the collection baskets, and sediment transport was collected for the first time. In addition to the main gravel sheet, two other surges moved along the flume downstream of the main surge. Figure 27 presents snapshots of these gravel sheets during Phase 1.

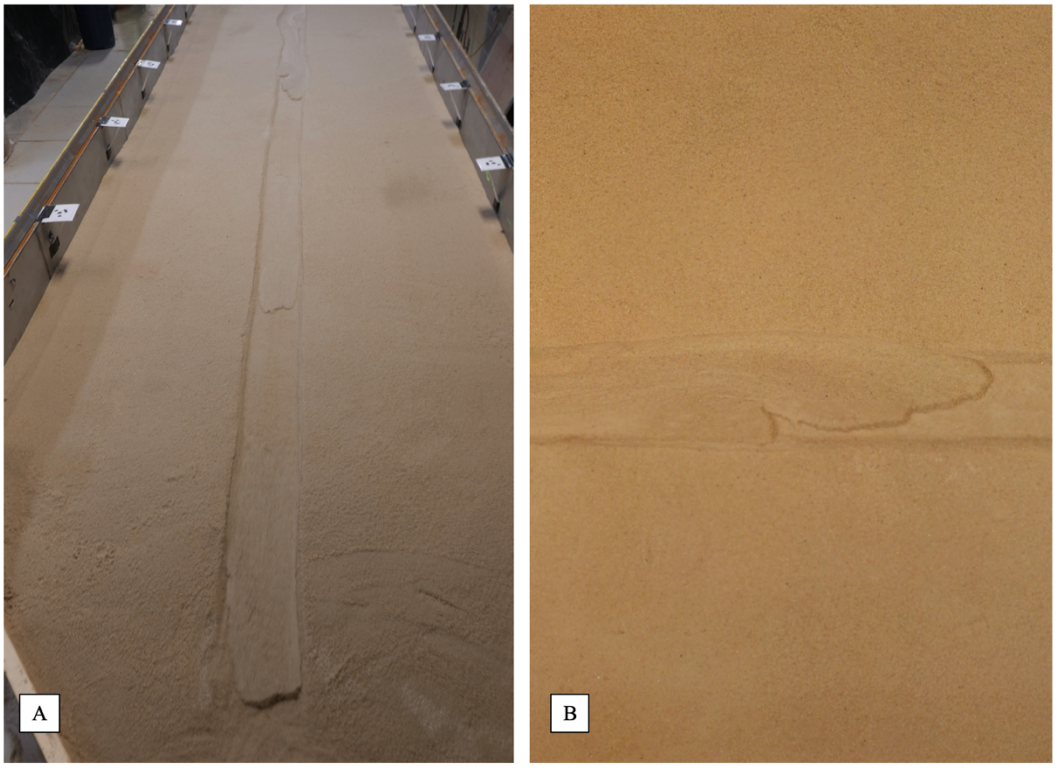


Figure 27. Gravel Sheets Observed During Phase 1 of Experiments (a) Prospective view of three gravel sheets after completing LMR_exp3; (b) Plan view of main gravel sheet after completing LMR_exp3

Phase 2 sediment transport varied greatly. In general, the 25-yr storms transported less sediment than the 100-yr storms. The average 25-yr and 100-yr sediment transport for Phase 2 was 0.58kg and 2.07kg respectively. One key transportation event that occurred in Phase 2 was the lack of sediment transport that followed experiment 10. Following experiment 10, as discussed in the methodology, the upstream configuration of the flume was changed. As a result, all sediment fed into the river was deposited upstream as a response to the configuration change, leading to negligible sediment transport for experiments 11-13. The configuration change was not the only time sediment was deposited upstream. Throughout the entirety of Phase 2 significant upstream deposition was occurring, so much so that it blocked off the main channel and resulted in the flow entering the floodplains. This blockage resulted in a large amount of sediment deposition within the floodplains.

Once the constrictions were added in Phase 3 there was a significant increase in the sediment transport. The average 25-yr and 100-yr sediment transport for Phase 3 was 4.52kg and 7.14kg

respectively. This means following the constrictions there was a 677% increase in sediment transport for the 25-yr storms and a 245% increase for the 100-yr storms.

4.4.2 Export Fractions

Based on the variable sediment transport results, the river was never in equilibrium, meaning the sediment that was leaving the flume was not equal to what was being put in. This was confirmed as the export fractions, which are the ratio of sediment exported versus imported, were never equal to 1. Based on the export fractions it is clear that prior to the constraints being added to the floodplain there was more sediment being added to the flume than taken away, meaning that sediment was accumulating within the flume during Phases 1 and 2. However, following the constraints being added, output was higher than input, meaning the river was degrading. Figure 28 presents the export fractions for each experiment. There is no export fractions reported for the 5-yr storm experiments, based on the sediment transport calculations these floods were expected to be near the threshold of motion for the sediment, and zero export was expected.

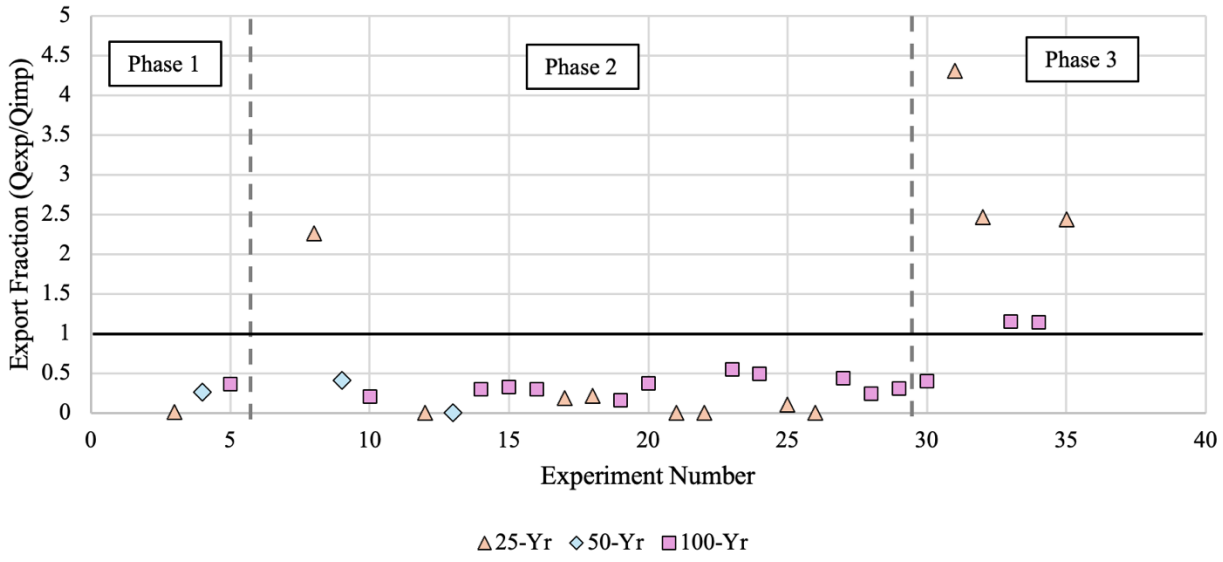


Figure 28. Export Fractions of Experiments

Through most of the experiments, the 25-yr storms had an export fraction smaller than the 100-yr year storms. Interestingly, in Phase 3, despite the 100-yr storms higher input load, the 25-yr storms had significantly higher export fractions. This is likely because the degree of transport was not controlled by the sediment input but rather the supply of sediment within the river channel.

4.4.3 Grain Size Distribution

The average grain size distributions for the unconstrained experiments in comparison to constrained experiments can be seen plotted alongside the standard deviations for each sieve size in Figure 29. The constricted experiments had a higher mass percentage of large sediment being transported which resulted in a lower percentage of small grain sizes to be transported. This was expected as velocity increased when the constrictions were added. This meant that the mobility threshold of the river increased and allowed larger grain sizes to be transported. It is likely that a similar quantity of finer sediments was transported, but by percentage it became less when compared to the entire mass transport.

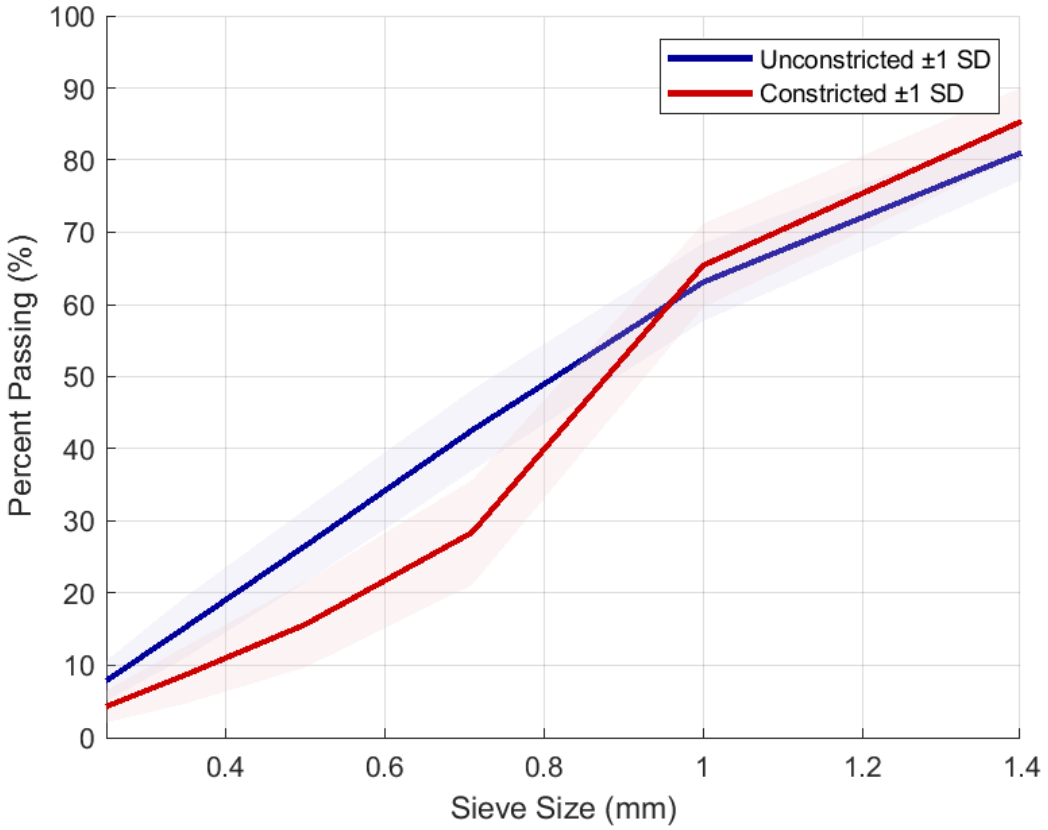


Figure 29. Grain Size Distribution of Unconstricted and Constricted Experiments

In general, the river was depositing more sediment than it was exporting until the constriction was added. Following the constriction the river flipped to exporting more sediment than was being deposited. The total sediment transport following the addition of the constraints increased significantly. These trends were evaluated and confirmed by looking at export fractions, total sediment transport, and grain size distributions.

4.5 Biological Features

4.5.1 Alfalfa Health

The alfalfa grown within the flume took 2-3 days to germinate. Healthy alfalfa persisted throughout the flume for the entire 68 days of experimentation that followed the seeding. Figure 30 presents the health of the Alfalfa throughout the flume study. The alfalfa grew up to 10 cm in height with the roots spanning the entire 4-5cm depth of the bed material. When extracted the alfalfa roots were interwoven creating a strong mat of roots and sediment. Figure 31 presents 34-day old alfalfa that was extracted from the flume.

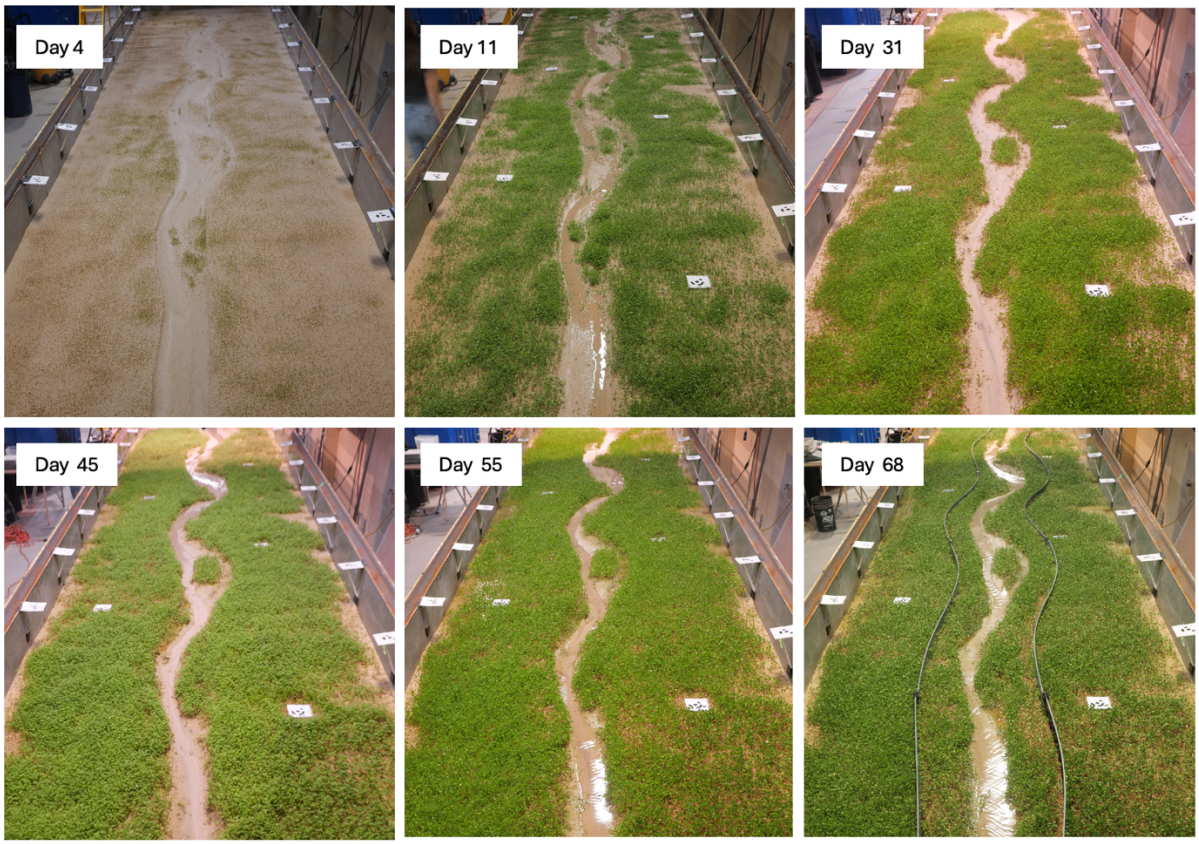


Figure 30. Alfalfa Growth in Flume

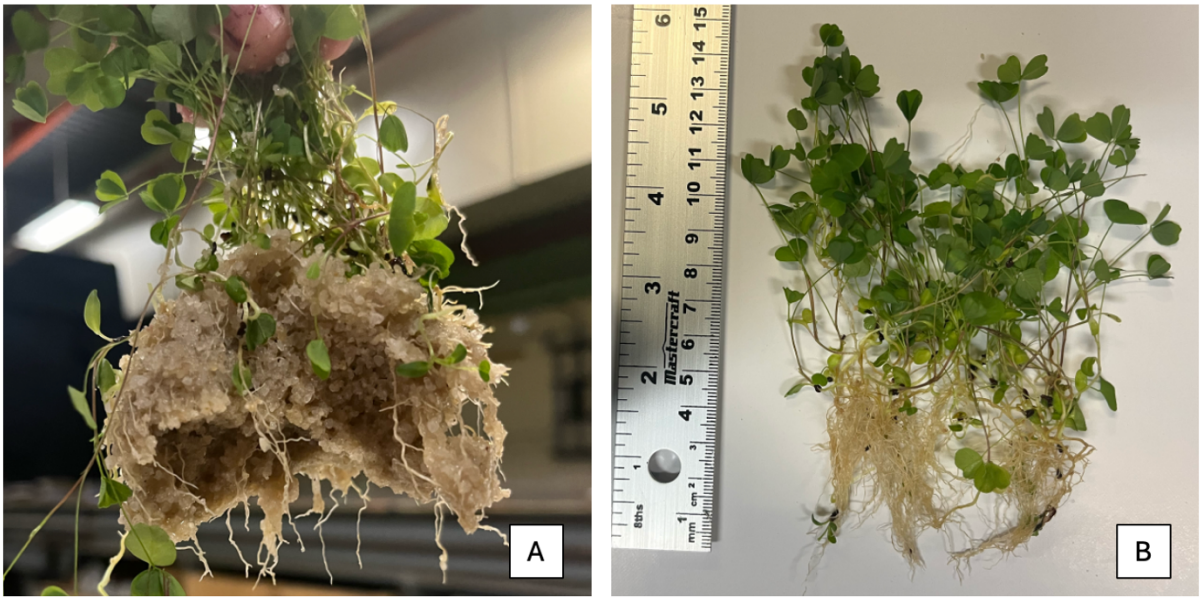


Figure 31. Alfalfa Extracted from Flume after 34 days of growth (a) Alfalfa roots and sediment; (b) Size of Alfalfa stems and roots

Initial die-off of alfalfa was observed 31 days after seeding. This death was primarily in low-lying areas of the flume where sediment depth was less than 5cm, or within the active channel on bars and islands. Figure 32 presents the locations of observed alfalfa death in comparison to the preliminary floodplain sediment elevations.

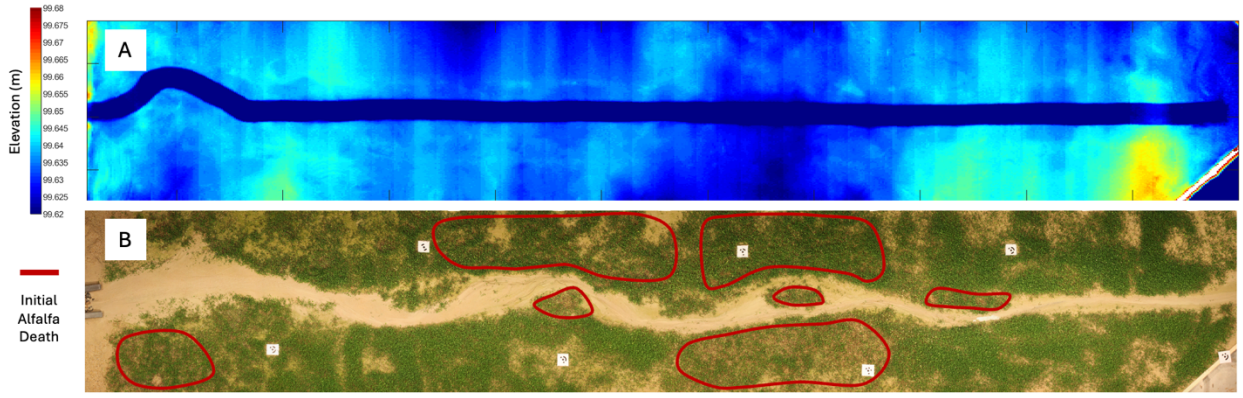


Figure 32. Observed Alfalfa Death Locations vs. Initial Floodplain Elevations (a) Detrended DEM from LMR_exp0; (b) Locations of initial Alfalfa death presented on stitched photo mosaic LMR_exp17

Despite this initial vegetative decline, the healthy alfalfa continued to grow until approximately day 45, from that point onward growth became stagnant and further die-off began. Additional vegetative death followed the placement of the constrictions during Phase 3 of the experiment.

Alfalfa was observed dying where the vegetation had been moved or crushed by the PVC sheets. One noticeable feature of the unhealthy alfalfa was white almost translucent leaves that appeared to have been sun bleached by the grow lights. Other Alfalfa that died off turned brown and shrivelled.

4.5.2 Alfalfa Bank Strength

The bank strength that the Alfalfa provided could not be quantified. Additional tests following the final experiment were completed to find a flow at which the Alfalfa would no longer be effective at protecting the banks. However, at flows of 2L/s, which are much greater than the 100-year flood (0.87L/s), no significant erosion into the floodplain was observed. The alfalfa provided enough bank strength for some riverbanks to be undercut by scour. An example of an undercut bank within the flume can be seen in Figure 33, which is an example from LMR_exp6 (5-yr storm).



Figure 33. Undercut Riverbank during LMR_exp6

During experimentation some banks that were eroded exposed the Alfalfa roots. Despite being exposed the roots were so densely packed that the Alfalfa remained on the bank. This then created additional bank protection as the Alfalfa slumped over and reduced the velocities surrounding these banks. Figure 34 presents an example during LMR_exp14 (100-yr storm) where roots were exposed but no further bank erosion occurred.



Figure 34. Exposed Alfalfa Roots Along Bank during LMR_exp14

4.5.3 Biological Growth

In addition to the purposeful vegetation growth, during the latter half of the experiments unintended biological growth occurred within the floodplains and non-active parts of the river channel. This biological growth left a widespread green hue across the flumes surface and may have contributed to increased bank stability, acting as a biofilm. Figure 35 presents an extreme example of the unintended biological growth within the flume.



Figure 35. Unintended Biological Growth

Chapter 5. Discussion

The goal of this research was to determine the effects of constricting a meandering river. To accomplish this, a meandering river was developed with alfalfa to increase bank strength and avoid the braiding of bars. Width constrictions were added to portray the addition of urban development limits. This section discusses how the experimental results such as morphology, streamflow dynamics and sediment transport relate to the broader context of this study, consider why the findings are significant, discuss limitations of the study, and state future research recommendations.

5.1 Morphology

The morphology of the river developed within the flume successfully represented the general form of a meandering river. The river had a sinuous single threaded nature, with pools along the outside of the bends and bars along the insides. However, with the sinuosity of the river being 1.04, the river is better described as sinuous (Mueller, 1968). The dynamics expected of a meandering river were also limited as no cut-off events occurred and bank erosion was limited following the introduction of vegetation.

There were only slight morphologic differences in the river following the addition of the constriction, i.e. the reduced channel width. However, this lack of planform change is not an indication that the constrictions did not affect the morphology of the river. Rather, the limited morphologic response can be attributed to the influence of the alfalfa, which had already constricted the river. The alfalfa functioned similarly to hard engineering structures such as riprap, armor stone, or gabion baskets, which stabilize banks and restrict natural channel evolution. When the PVC barriers were installed, their impervious nature enabled them to further constrict the river in ways that the alfalfa had not. While the alfalfa had reduced natural river processes through limiting bank erosion, it did not prevent channel and floodplain interactions. The addition of the PVC constrictions limited the lateral flow of sediment and water into the floodplains. This resulted in the channel entrenchment and reduced channel width. In addition to channel narrowing, the height of the channel's natural levees appeared to increase. This pattern resembles sedimentation processes that have occurred in the Mississippi river system over the last century. As the flow of water and sediment was restricted from going beyond the barriers,

more sediment settled out into the sections of the floodplains that were not restricted (Fitzpatrick et al., 2009). Had the barriers more severely constricted the channel, this may have reduced rather than enhanced natural levee formation. Overall, the rivers morphology changed when the constrictions were added, however further changes may have occurred if the river hadn't been excessively stabilized by the alfalfa.

5.2 Streamflow Dynamics

As the quantity of discharge entering the flume was controlled, the quantity of water within the flume was as expected. Despite the control of the discharge entering the flume, the constrictions effect on the river's streamflow was significant. Since the floodplains water table was reduced following the addition of the PVC sheets, greater flow was sent through the active channel. This increase in discharge, increased both the channel depth and velocity throughout the river. These streamflow dynamics then resulted in significant sediment transport differences and limited morphology differences. The water table drop in the floodplains also suggests there was a reduction in the extent of the hyporheic zone.

5.3 Sediment Transport

Despite the variability of sediment transport throughout the 35 experiments, sediment transport within the river still significantly increased following the installation of the floodplain constraints. This increase was primarily due to the mobilization of sediment already present within the channel, rather than bank erosion. Minimal bank erosion was observed because alfalfa provided excessive bank strength. The constrictions reduced flow past the barriers, resulting in a greater volume of water through the main channel. This increase likely elevated the channel's velocity and shear stress, surpassing sediment mobility thresholds, and augmenting the channels sediment transportation capacity. During Phase 2, within the first four meters of the flume, excessive sediment was deposited as indicated by the DoD analysis and thalweg profiles. This abundant sediment supply also helped to facilitate the increase in sediment transport as there was increased availability. Only six constricted experiments were conducted; if more had been completed, it is plausible that the sediment supply would have diminished, leading to further channel incision and reduced sediment transport rates.

5.4 Effects of Constricting a Meandering River

Overall, following the introductions of river constrictions, there was a decrease in the floodplain water level. This resulted in an increase in velocity and water depth within the active channel, which in turn significantly increased sediment transport through erosive processes. The increased sediment transport resulted in channel incision which ultimately reduced channel width and further increased water depth. The addition of the constrictions also reduced floodplain and channel interactions past the barriers. No sediment or flow was able to spill over and replenish the floodplains beyond the barriers. This also resulted in larger quantities of sediment inundating the limitedly available floodplain areas. Although effects were observed following the constrictions, the extents were limited, because the river was previously constrained by the addition of vegetation along the banks and throughout the floodplain.

The effects caused by constricting the river's floodplain, were consistent with the outcomes suggested by previous studies on river constriction. Garcia Lugo et al., (2015) and Amini et al., (2020) determined strong confinement produced regular planforms while low confinement allowed for more complex planforms to develop. As the developed river was constricted by both alfalfa and PVC sheets it had little meander evolution throughout Phases 1 and 2. The floodplain was not reworked through cut-off events, bank erosion, bar deposition, and the creation and destruction of floodplain structures, this suggests that the complexity of this river system was limited. Thus, confirming the theory that high confinement results in low planform complexity. Additionally, Li et al., (2024) who studied constrained sections of the Yellow River, determined that in constricted sections of the river the sinuosity was reduced and represented a transitional zone between straight and meandering. This corresponds to our findings as the expected sinuosity of the river was 1.67, however the actual developed river had a sinuosity of approximately 1.04. The sinuosity of 1.04 is within the zone between meandering and straight rivers, again confirming Li et al., (2024) findings. The one place that our results did not confirm previous literature results is when compared to Moghaddem & Rennie (2018) who found that a partially constrained river in Ottawa experiences greater bank instability. Because of the extensive bank strength provided by the Alfalfa this could not be confirmed.

In addition to the previously confirmed theories on the implications of constricting a meandering river, the results from this study collectively suggest that constricting a river includes the following outcomes:

a) Significantly decreases floodplain and river connectivity
   - Cuts-off floodplain sedimentation past barrier extents
   - Increases floodplain sedimentation within available floodplain
   - Restricts the flow of water over floodplains
b) Alterations in channel flow regime
   - Increased discharge, velocity, and flow depth
c) Reduced channel width
d) Increased sediment export
e) Reduced hyporheic exchange

5.5 Significance and Implications of Findings

This research strengthened our understanding on the effects of constricting a meandering river and expanded on laboratory methods used to create stable and self-sustaining meandering rivers. These results will influence future river management practices and improve restoration efforts.

5.5.1 Implications on the Effects of Constricting Meandering Rivers

The implications of constricting a meandering river, as established in this study, are likely already present in many high energy gravel bed rivers. This prevalence is a result of the rampant anthropogenic constraints on river systems globally. Constricting riparian zones reduce the beneficial functions that riparian buffers provide such as maintaining water quality, erosion control, biodiversity, and resilience.

One key consequence that constrictions bring to a meandering river, as implied by the results of this study, is a reduction in biodiversity and habitat abundance. By preventing sediment from spreading across floodplains, constrictions decrease the supply of nutrient rich sediments which are essential for supporting healthy riparian ecosystems (Opperman et al., 2017). Conversely, in areas where floodplains remain connected, abundant floodplain sedimentation can cause terrestrial and wetland habitats to be smothered (Fitzpatrick et al., 2009). Constrictions can also alter a river's flow regime, negatively impacting existing riparian biota. For example, increased

velocities reduce macrophyte biomass (Chambers et al., 1991) and disrupt flow conditions necessary for maintaining fish habitat (J. Li et al., 2019). The loss of overbank flow deprives wetland ecosystems of the water they require (Warner, 2022) and diminishes hyporheic exchange, an important source of nutrients (Boulton et al., 2010; Tonina & Buffington, 2009). Additionally, increased sediment transport can remove vital spawning gravels for fish (Taylor et al., 2019) and overwhelm downstream ecosystems with excessive sediment deposition.

The second impact of constrictions, highlighted by the results of this study, are reduced flood protections. Floodplain constrictions which increase channel discharge and flow depth, as they did in this studies flume experiments, cause an increase in a channel's sediment transport capacity. This capacity can then result in detrimental quantities of sediment and debris being transported during extreme flood events. This transport can cause damage to buildings, dams, bridges and other infrastructure surrounding the river (Vázquez-Tarrío et al., 2024). Limiting the channels' ability for flow to spill into a floodplain makes it more vulnerable to flood events. Without the energy dissipation of water spilling into a floodplain, elevated erosion within the river will occur, again increasing flood risks to adjacent infrastructure (Klijn et al., 2018). This lack of lateral freedom, emphasized by excessive natural levees, will result in river channels that are more sensitive to uncertainties in discharge, ultimately reducing the robust and resilient nature of rivers.

5.5.2 Importance of Alfalfa Health in Laboratory Studies

By applying vegetated bank stabilizations within laboratory methods, this study was able to explore how vegetative structures influence the development of channel morphology. This provides new insights into the importance of understanding and controlling the health of vegetation used in experiments. Prior to the experiments completed in this study, the variability in erosive conditions produced by the same vegetation in flume studies was unclear. Previous research did not cover the complexities of Alfalfa health. Alfalfa is easy to grow, as a result it is easy to think that alfalfa is either going to be dead or alive, with the main controlling factor being density of seeding. Following this research, it is now clear that Alfalfa is significantly complex and variable, and understanding health, density, and age is very important in determining the effect that vegetation will have on the river systems.

The Alfalfa grown in this study did not die off after 15-20 hrs of running the flume as it did during the 2009 experiments completed at the University of California Berkeley (Braudrick et al., 2009). Instead, healthy alfalfa persisted throughout the flume without re-seeding. The majority of alfalfa remained healthy for over 200 hours of flume run time which occurred over 68 days. Prior to experimentation, based on the results from the Braudrick et al., (2009) study, die off was expected. This expected die off was thought to be caused by a lack of nutrients supplied to the alfalfa continued growth. However, this study did not introduce additional nutrients, and the Alfalfa did not die.

A plausible hypothesis for the die off in the 2009 study is that the alfalfa was being exposed to excessive water that resulted in roots not establishing and potentially being rotted. Alfalfa is very sensitive to excessive soil water, and experiments have demonstrated that root growth stops during flooding (Thompson & Fick, 1981). This sensitivity is due to excess soil water stress and Phytophthora root rot (Alva et al., 1985). Plants produce oxygen; however, they also need oxygen to support metabolism, specifically in roots. Excess water limits the availability of oxygen causing growth disturbances (BORU, 2003; Zhang et al., 2019). Waterlogging can also result in an increase in plant ethylene levels which leads to reduced root and shoot growth (Najeeb et al., 2018).

During the experiments completed throughout this study, on experiment days, Alfalfa was exposed to 6 h of saturated soil conditions. On days experiments were not completed the Alfalfa was only watered when the soil became significantly dry. It is likely that these conditions, where the soil was allowed to drain, better supported alfalfa growth. When initial death occurred after 31 days of alfalfa growth it was concentrated in low-lying areas with increased soil saturation. This further supports the theory of excessive soil water stress being a cause of Alfalfa death and reduced development.

Although the Alfalfa was successfully grown in this study, it is also one reason why the desired degree of river development and bank erosion was not achieved. Based on the successful migration produced in the 2009 studies it may be desirable to limit the growth of the Alfalfa. Another reason why river development was not achieved may be due to the density at which the Alfalfa was grown. Reduced seeding density may decrease the root matting and allow more erosion and river development to occur.

5.5.3 Recommendations for River Restoration

The results of this study highlight the importance of establishing sufficient riparian buffers and understanding the role of vegetation applications within river restoration. In areas where it is safe to do so, future restoration efforts should prioritize creating room for rivers, removing infrastructure in adjacent floodplains, and reducing engineering controls within the channel. Creating these buffers will not only promote biodiversity but also improve river resilience, ensuring long-term public safety. In places where a sufficient riparian buffer is not feasible, maximizing floodplain connectivity and riparian spaces is key, while also maintaining flood protections.

This approach helps avoid falling into the shifting baseline syndrome, which explains how over generations the perception of a river's natural state becomes distorted due to the inherited degraded conditions (Brierley & Fryirs, 2022; Pauly, 1995). By restoring riparian buffers, alongside additional restoration efforts, a new baseline can be established to aid in preserving and promoting a river's natural processes. Prioritizing a river's natural processes will allow it to become more resilient as the river will be able to appropriately adapt to the disruptions it experiences.

In addition to these buffer considerations, vegetation should be chosen carefully in restoration projects to reflect the natural conditions of each site. Vegetation should be chosen for not only its ecological value but to also correctly correlate to a river's required bank stabilization. As demonstrated in this study, choosing the incorrect density or plant species for a specific river system can disrupt natural processes, either excessively inhibiting or enabling erosive processes.

5.5.4 Recommendations for the City of Calgary's River Management

Based on the research conducted, it is essential that the City of Calgary enforces its current 50-meter buffer regulations and continues investigating the appropriate riparian buffer width for the Bow River. One major concern highlighted in this study, that will persist with continued development along the Bow River, is potential decreased fish populations. The Bow River is a host for many substrate spawning fish such as Rainbow and Brown Trout (Government of Alberta, 2019). Floodplain constraints will disrupt these important gravel bed spawning habitats through increased sediment export.

To better balance the City's economic growth with public safety and environmental health, strong and effective provincial and federal policies for riparian buffer management are required. Unfortunately, such policies are rarely a quick solution. In the short term, public education programs would be an impactful solution for the city. The efforts of a small group of fluvial geomorphologists and engineers advocating for the importance of the Bow River's floodplains are unlikely to outweigh the influence of profit-driven industries like land development. Public education on this topic can generate greater influence; when residents understand the value of riparian buffers, public opinion and outcry can hold decision makers accountable.

5.6 Limitations

Throughout the course of this research many limitations of were encountered. These limitations were mainly imposed by the methodologies used to complete the experiments.

Although Agisoft Photoscan successfully stitched together 14 experiments aerial images, that also means 21 were not successful. Multiple factors contributed to these issues, including inconsistency in the aerial photos taken as well as limitations of the software to interpret the images correctly. The issues encountered during the aerial imagery processing resulted in a lack of analysis for short-term changes within the river. The methods used to collect the topographic information also restricted the ability to have a detailed view of the floodplain morphology as the methods could not isolate the alfalfa and produce accurate floodplain topography. This limited the ability to investigate specific features and forms of the floodplain and how these were affected with the introduction of floodplain constrictions.

Another significant limitation of this study was the Alfalfa strength. The alfalfa provided so much bank strength that the river was physically constricted by the Alfalfa prior to the barriers being added. This Alfalfa strength resulted in little meander evolution. As a result, minimal morphological effects of constriction were identified.

The last methodological limitation within the study was a result of the valve precision. The valve was inconsistent in its flow control, meaning that even when the same hydrographs were run, the discharge and length of time at a specific discharge differed. The valve could not complete smooth and small discharge intervals changes. The minimum flow the valve was able to run without completely shutting off was around 0.2L/s. This meant that for all storms the start and

end of the hydrograph was flat with a baseflow of around 0.2L/s. This was most significant when running the 5-yr storm, as the flow remained fairly consistent for the entire 6-hr run time.

5.7 Research Gaps Future Research

Several research gaps remain. Methodologically, further research is needed to determine the ideal density and health conditions of Alfalfa to produce self-sustaining meandering rivers, that develop laterally and downstream over time. Additionally, aerial imagery collection methods need to improve to get consistent and accurate topographic results. Establishing methods to remove Alfalfa from aerial imagery and topography would significantly improve our ability to evaluate the morphology of floodplains.

Following these methodology improvements further experiments should be completed to determine the morphological effects of constricting a river that would otherwise have active meandering throughout its floodplain. Ideally, different constriction configurations can be evaluated including partially constricted scenarios and different constricted widths to better establish the trade-off between riparian buffer width and channel morphodynamics.

Chapter 6. Conclusion

This thesis set out to investigate the effects of floodplain constrictions on a meandering river. This was achieved through novel flume experimentation; using a physical model designed to represent characteristics of the Bow River in the City of Calgary. The experiment scenarios included non-vegetated, vegetated, and vegetated with constrictions. While alfalfa has been used in previous flume studies, this research was the first of its kind to not only simulate a natural meandering river, but also assess its response to floodplain constrictions.

The results were shaped by certain experimental limitations, most notably the bank strength provided by alfalfa, which inhibited meander evolution, and may have masked some constriction effects. Additionally, methods used to capture and process aerial images, were inconsistent and only intermittently effective.

Despite these limitations, the study found that floodplain constrictions significantly reduce river-floodplain connectivity, alter a channels flow regime by increasing discharge and flow depth, increase sediment transport, and narrow channel width. The results also reinforce previous research, emphasizing that constrictions lower a rivers sinuosity and reduce planform complexity. Moreover, this research expands current understanding on how vegetative structures influence the development of channel morphology, highlighting the importance of understanding vegetative health for both flume experiments and real-world restoration projects.

The studies implications imply that floodplain constrictions in meandering rivers negatively affect riparian ecosystems, lowering biodiversity and destroying habitat abundance. Constricting meanders will also increase flood risks, making flooding more costly for infrastructure and human health. These outcomes can be avoided by prioritizing the protection and creation of room for rivers during restoration efforts and developmental planning. River engineers carry the responsibility of integrating ecological considerations into project and should act as stewards of sustainable river management. At a broader scale, robust riparian buffer policies and regulations need to be adopted by governing bodies globally. Future research should further explore the conditions necessary to create mobile meandering rivers in flume settings, to further evaluate optimal riparian buffer widths.

As demonstrated by this study, river resilience requires sufficient floodplains.

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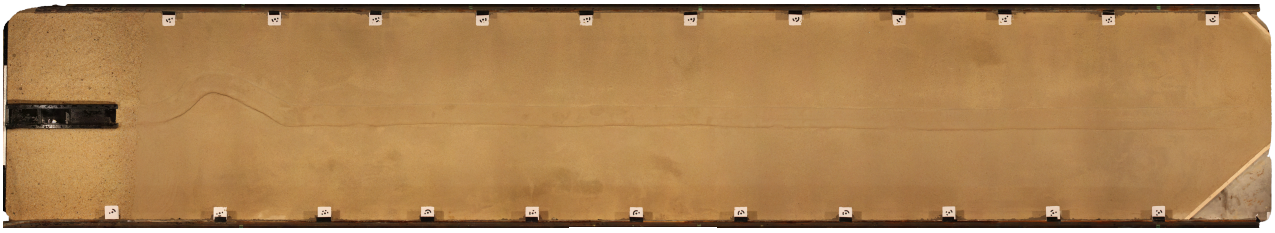
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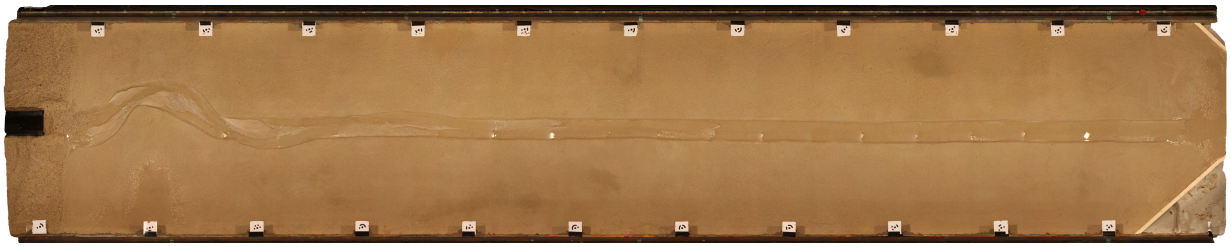
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Appendices

Appendix A – Stitched Photo Mosaics



LMR_exp_0



LMR_exp_1



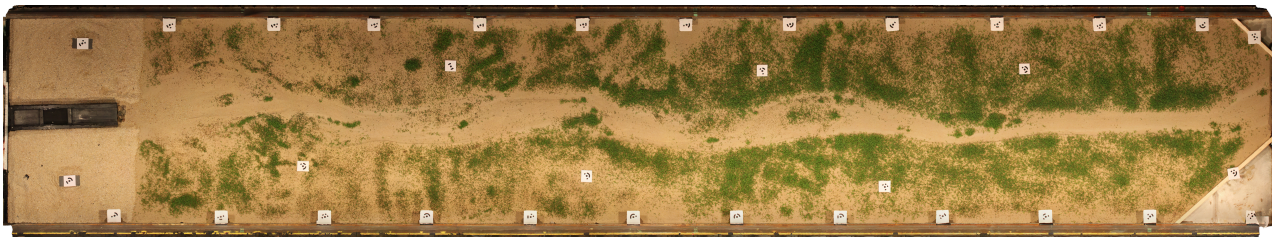
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LMR_exp_3



LMR_exp_4



LMR_exp_5



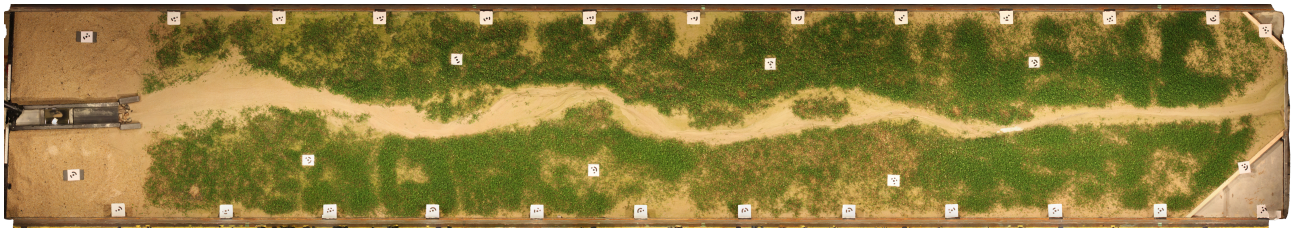
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LMR_exp_9



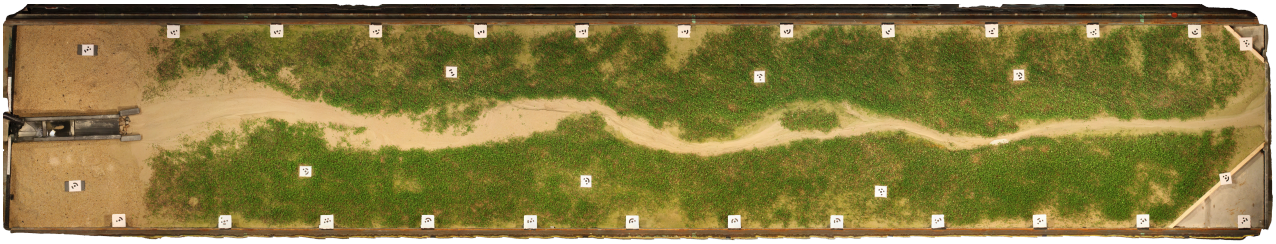
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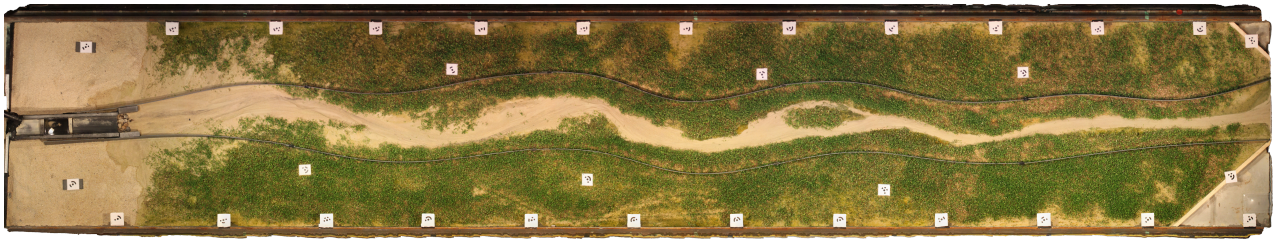
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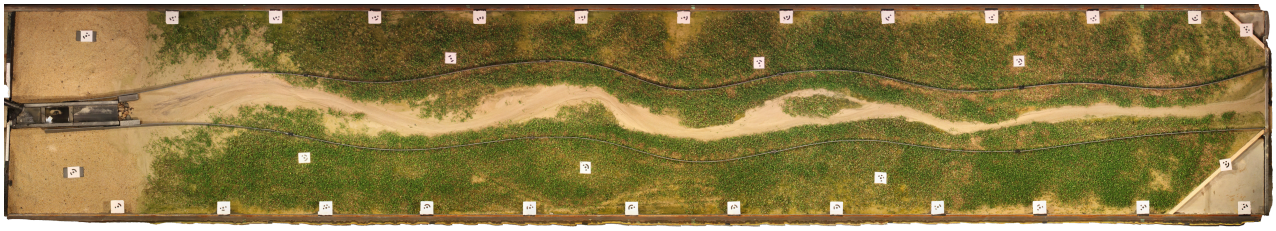
LMR_exp_18



LMR_exp_25

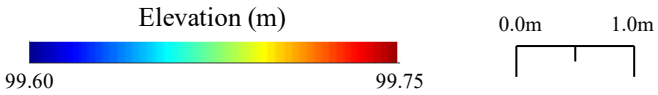


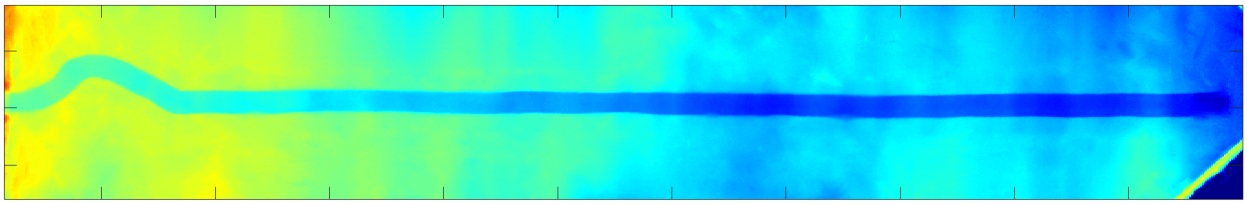
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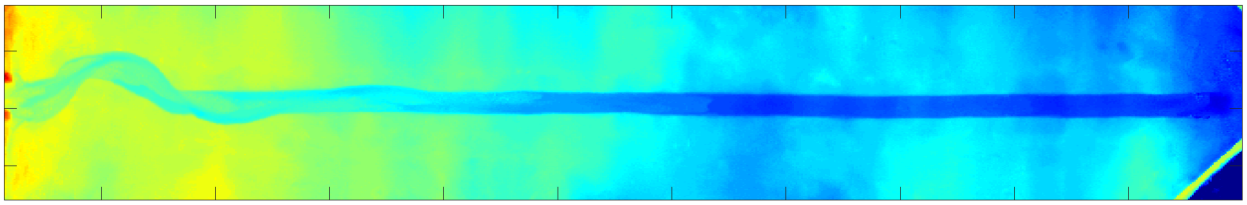
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Appendix B – Digital Elevation Models

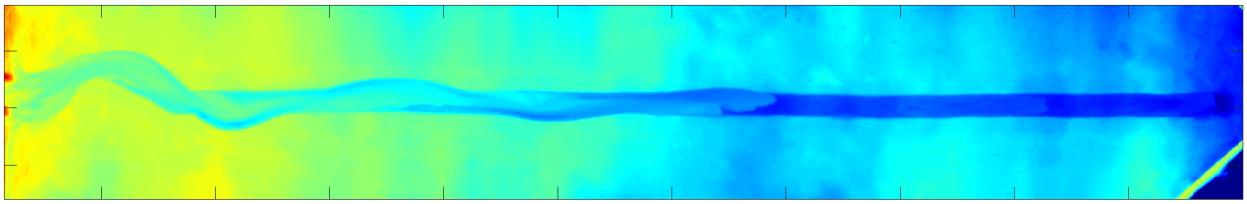




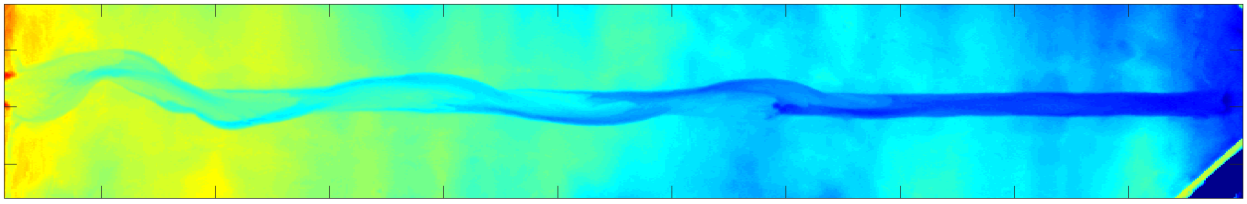
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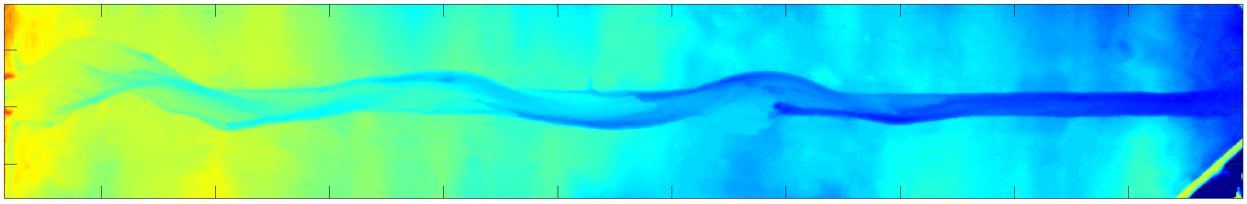
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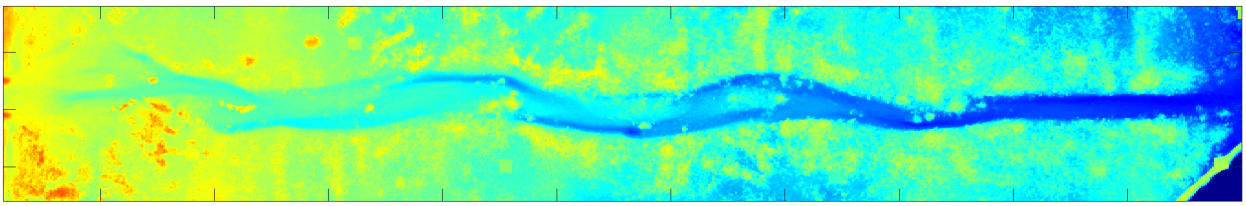
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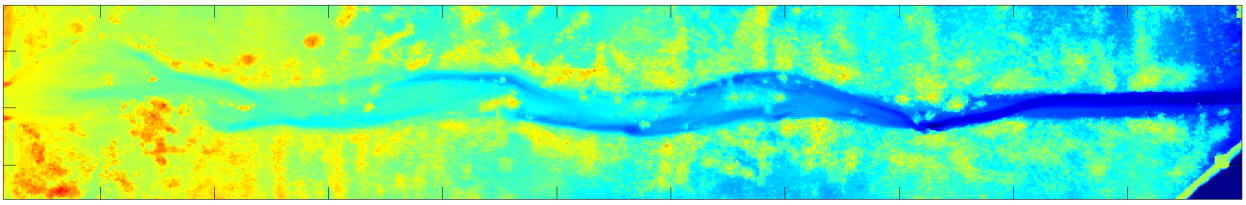
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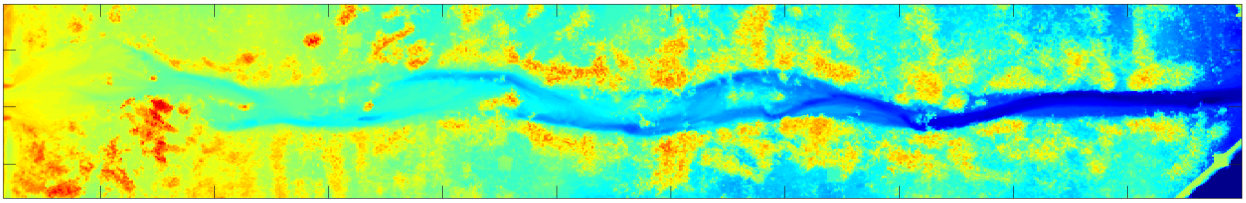
LMR_exp_4



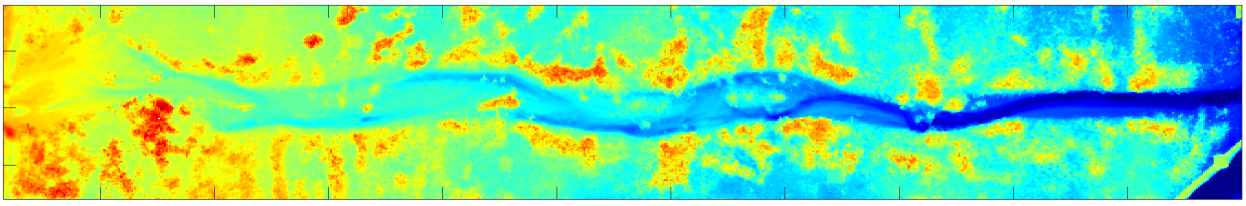
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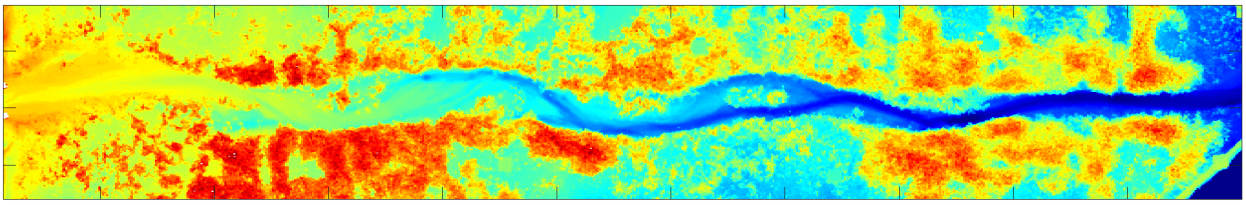
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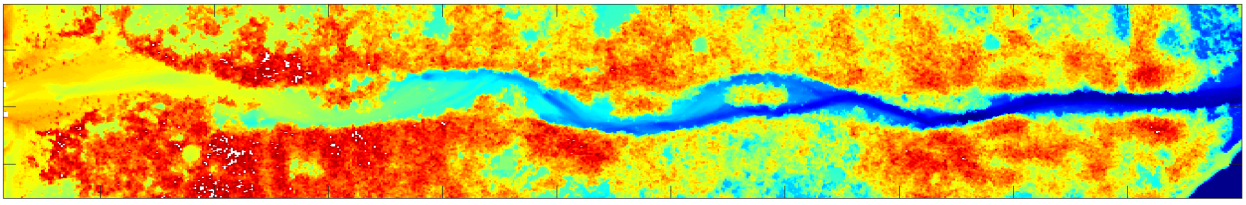
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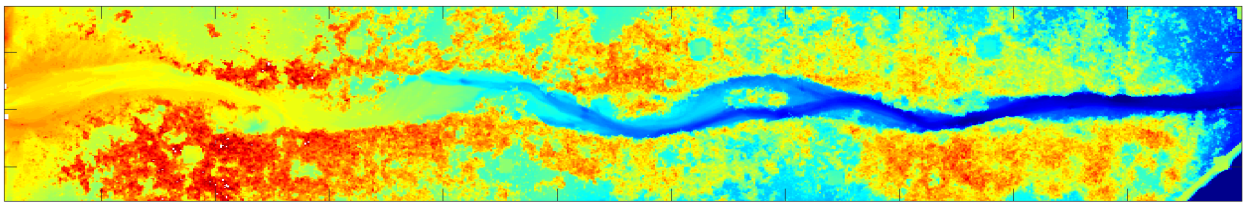
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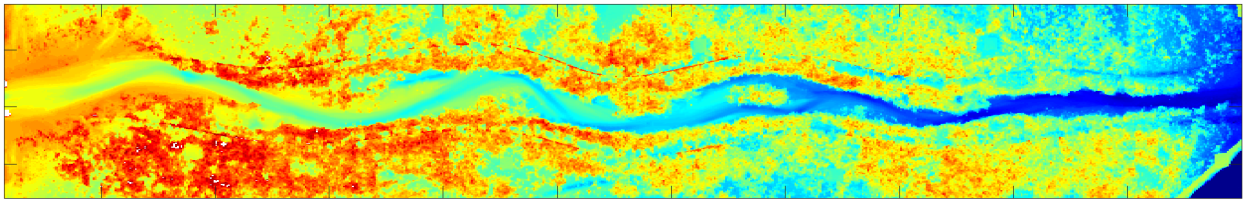
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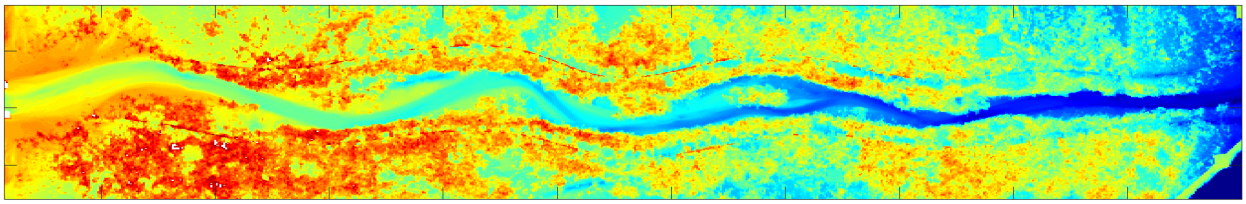
LMR_exp_18



LMR_exp_25



LMR_exp_33



LMR_exp_35

Appendix C – Jumping Pound Creek Channel Characteristics

The following data outlined in Table A, was generated using a combination of various aerial imagery analysis techniques and calculations.

Table A. Jumping Pound Creek Channel Characteristics

Parameter	Units	Value
Channel Width (T)	m	19.2
Channel Depth (y)	m	1.07
Peak Discharge (Q)	m^3/s	23.4
Slope (S)	m/m	0.0049

The channel width of Jumping Pound creek was determined using aerial imagery from Google Earth Pro. This was completed by taking measurements of 22 cross sections found along a 5.62 km stretch of Jumping Pound creek. Based on this method after averaging all cross-sectional width values a representative width of 19.2 m was determined. Figures A and B present the section of the river that was assessed and the locations of the cross sections.

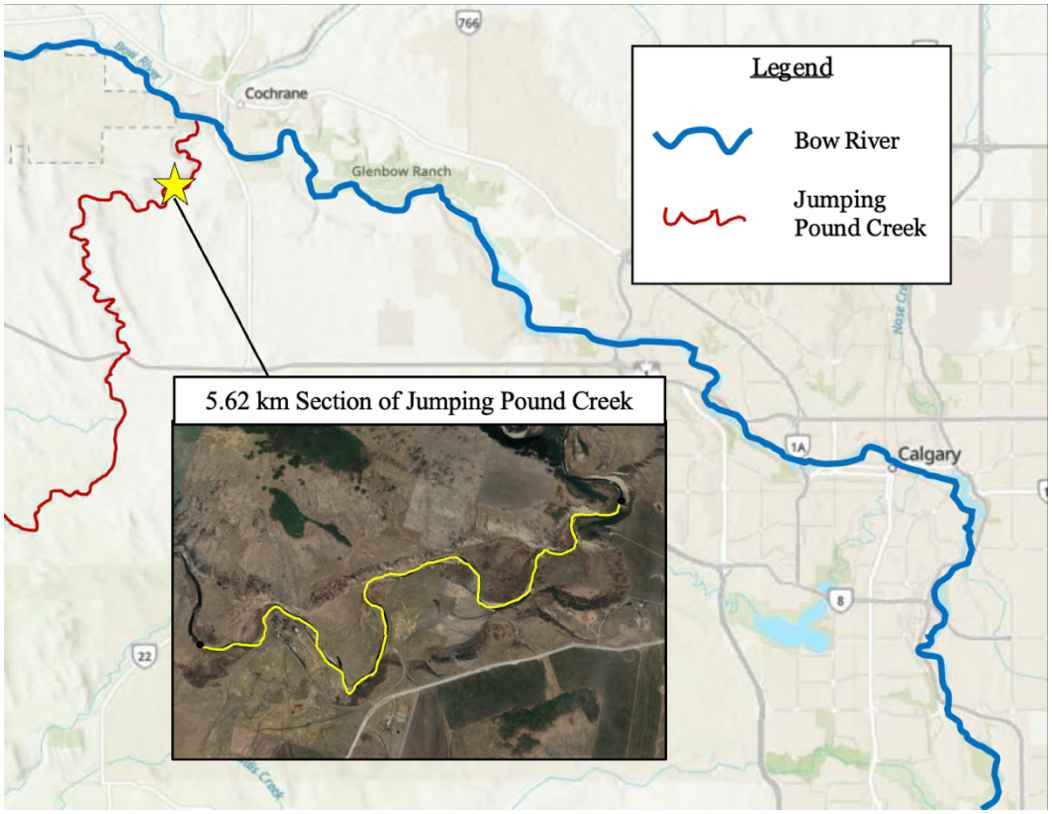


Figure A. Section of Jumping Pound Creek Used for Data Generation

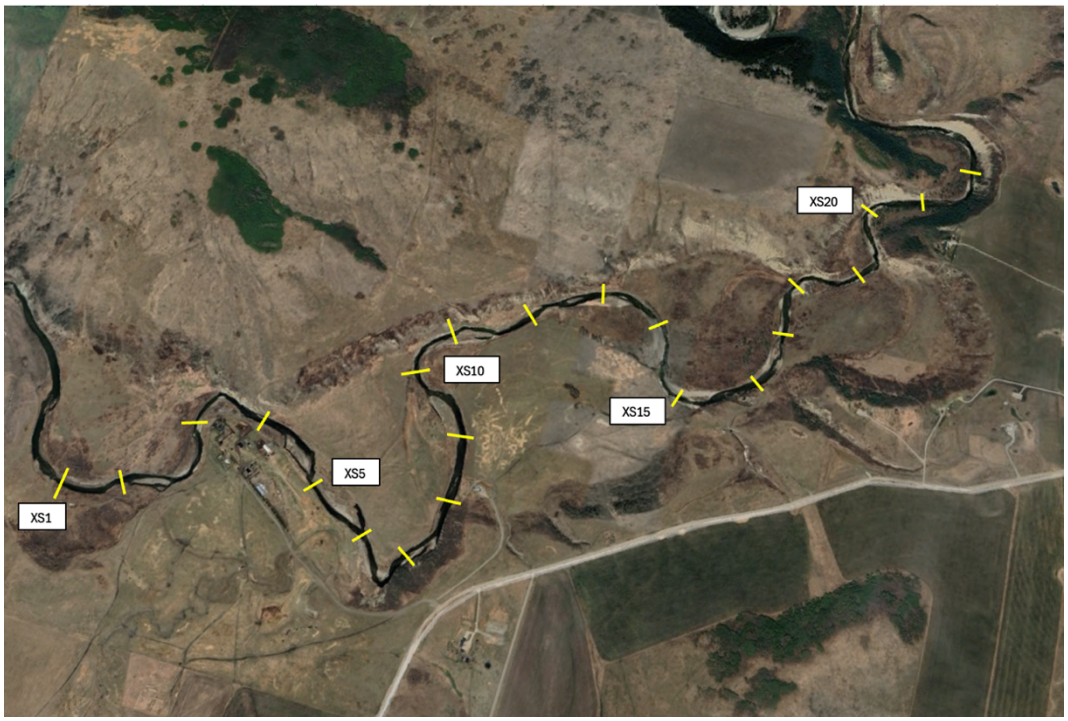


Figure B. Cross Section Locations Along Jumping Pound Creek

The slope of Jumping Pound creek was determined to be 0.0049 (-) or 0.49% by using Google Earth Pro elevations. The upstream bed elevation (Z_{up}), downstream bed elevation (Z_{down}), and total channel length ($L_{channel}$) were used in the following formula to calculate channel slope:

$$S = \frac{Z_{up} - Z_{down}}{L_{channel}}$$

The peak channel discharge was taken by finding the maximum discharge value recorded by the Jumping Pound Creek Stream Gauge (O5BH013) over the last 5-years. This occurred on June 14th, 2022, with a peak discharge of 23.4 m^3/s (Government of Canada, 2025). Following the determination of the peak discharge, a depth value was calculated using Manning's equation. This was completed using excel and changing the depth value until an appropriate discharge value was met. The Mannings equations used is as follows:

$$Q = \frac{A}{n} * R^{\frac{2}{3}} * S^{\frac{1}{2}}$$

Where Q is the discharge (m^3/s), A is the area (m^2), n is the Manning's n coefficient (0.04), R is the hydraulic radius (m), and S is the slope (-). The Manning's n was chosen using values presented in Chow (1959), a book on open channel hydraulics. A depth of 1.07 m was the result of this analysis. This number was then confirmed for viability by comparing it to the corresponding water depth value from June 14th, 2022, which was 1.17 m. The value of 1.17 m was not used as the actual water depth as it does not correspond the average channel width, however the depths were compared to ensure the numbers were within a factor of magnitude of each other.

Appendix D – Jumping Pound Creek Storm Re-occurrence Intervals

The 5-yr, 25-yr, 50-yr and 100-yr storms for Jumping Pound creek were determined by evaluating the creeks extreme yearly storms, of which the Government of Canada stream gauge (05BH013) provided 32 years of data. Since there was only 33-years of data, and 50-yr and 100-yr storm sizes needed to be determined, a logarithmic equation was used to extrapolate storm sizes greater than 33-yrs. Figure C presents a graph of storm reoccurrence intervals compared to stream discharge.

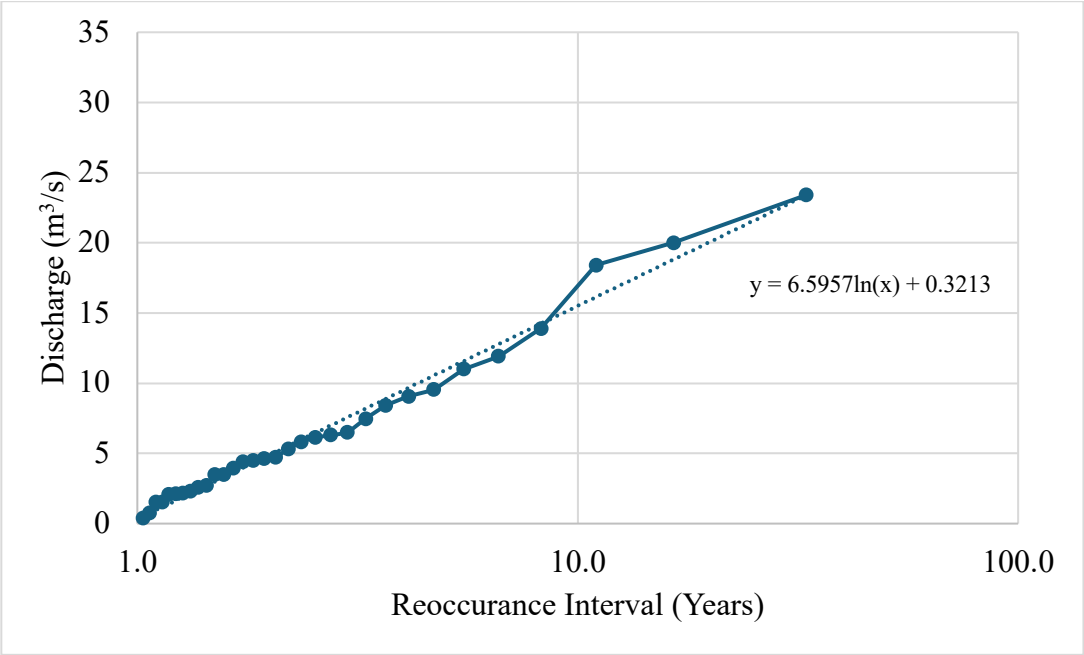


Figure C. Jumping Pound Creek Storm Reoccurrence vs. Discharge

Based on this relationship the discharge for the 5-yr, 25-yr, 50-yr and 100-yr storms was determined, these values are all presented in Table B.

Table B. Jumping Pound Creek Storms

Storm Reoccurrence	Discharge (m^3/s)
5-yr	10.94
25-yr	21.55
50-yr	26.12
100-yr	30.70