THE FORMATION AND ADJUSTMENT OF A POOL-RIFFLE SEQUENCE IN A
GRAVEL BED FLUME

by

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Abstract

Pool-riffle sequences are a dominant morphological feature found in a wide range of fluvial environments. The hydraulic and sedimentological complexity that they impart provides important aquatic habitat, resulting in their increasing implementation in river restoration projects, despite the fact that there are still many inconsistencies in the literature relating to the processes involved in their formation and maintenance. The main research objective was to study the formation, adjustment, and maintenance of pool-riffle morphology in gravel bed rivers. A variable width, mobile-bed flume was configured as a model of a pool-riffle reach in East Creek, British Columbia, and the development of a pool-riffle sequence under bankfull discharge, and subsequent adjustment to increased discharges were studied. The central pool-riffle sequence developed around a major width constriction and persisted in that location throughout the entirety of the experiment, increasing in amplitude in response to increased discharge. Bed texture was initially quite variable, but became relatively constant throughout the entire flume near equilibrium, including the pool and riffle. Hydraulic parameter reversals from low to high flow were observed between the pool and riffle, including water surface slope, section averaged velocity, and bed shear stress. Particle mobility was higher in the pool, but the virtual velocities of mobile particles were constant until the highest discharge. Evidence of secondary flow patterns was recorded in the pool, which could suggest a maintenance process in addition to velocity reversal. These results should inform future studies and design projects on pools and riffles, especially in relation to their behaviour during flood events.
Lay Summary

Riffles and pools are alternating areas of high and low river bed elevation respectively. They are an important source of fish habitat and are often added to river restoration designs, even though there are still a lot of unknowns about how they are formed and how they adjust during floods. It can be difficult to collect data in a river during flooding, so the features were studied in a physical model of a river in a laboratory setting. A pool-riffle sequence was developed under a constant water flow rate, then the flow was increased to observe how the sequence would adjust to higher floods. The pool-riffle sequence developed around an area where the channel narrowed, and persisted through the experiment, deepening in response to the higher flood levels. Differences in flow and sediment parameters between the pool and riffle were studied at each flow level.
Preface

This thesis is original work created by Emma Buckrell, based on experimental work completed in the summer of 2016 in the BioGeoMorphic eXperimental Laboratory at the University of British Columbia, Vancouver, Canada under the supervision of Marwan Hassan. None of the text has previously been published.

The flume configuration used for the experimental work, and the associated sediment mixture grain size distribution, discharge levels, and sediment feed rates, were designed by Shawn Chartrand. The DEM analysis code was written by Shawn, and the grain size analysis codes and hydraulics analysis code were modified from codes written by Shawn. The experimental design section of Chapter 2 was based on Chapter 3 of Shawn’s PhD thesis (Chartrand, 2017). The experimental procedure, data collection, and data analysis were all designed and performed by Emma Buckrell with some assistance in the lab during execution of the experiment.

LabView codes used for flume cart control, collection of DEMs, bed topography, and collection and processing of light table data were written by Andre Zimmermann and modified by Shawn Chartrand.

Gravel tracers were assembled by Elli Papangelakis. The acrylic boat used for pool-riffle bed photography and the bed load samplers were constructed by Ryan Buchanan. Additional laboratory support was provided by Rick Kettler.
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Chapter 1: Introduction

1.1 Background

Pool-riffle sequences are the dominant morphologic feature in rivers with a gradient below 1.5% (Montgomery & Buffington, 1997) and are found in a wide range of environments, including both alluvial and bedrock channels (Leopold et al., 1964). The topographic lows and highs provide substrate and hydraulic heterogeneity, making them an important source of habitat for fish and benthic invertebrates. Differences between pools and riffles are most apparent under low-flow conditions, as variations in water surface slope, and therefore friction slope decrease with increasing stage (Thompson, 2010). At low stage, pools are deep areas with low velocities and divergent flow, whereas riffles are generally believed to have faster velocities, higher water surface slopes, higher competence, and convergent flow (Leopold et al., 1964; Clifford & Richards, 1992; Sear, 1996). Many river rehabilitation projects aim to re-establish natural pool-riffle sequences; however, there are disagreements in the literature on the morphodynamic processes that shape them, and resultantly, there is no widely adapted, standardized, systems approach for their design (Wade et al., 2002). The apparent complexities in the maintenance processes and closely linked sediment transport processes surrounding pool-riffle sequences truly illustrate the importance of considering form-process interactions during restoration projects, especially those where pool-riffle sequences are being artificially constructed with the goal of increasing channel stability and the quality of aquatic habitat. Our ability to foster natural self-maintenance of these sequences will become increasingly vital as urban hydromodification continues to increase, and climate change further impacts natural channel parameters and processes.
Literature relating to pool-riffle morphology, theories on the processes of pool-riffle formation and maintenance, the sedimentology of pools and riffles, and the sediment transport processes around these features is summarized below.

1.1.1 Pool-Riffle Morphology

Pools and riffles have been described as topographic low and high areas of the channel bed that are defined relative to each other (Wohl, et al., 1993; O’Neill and Abrahams, 1984), and as analogous to meandering in the vertical direction (Keller & Melhorn, 1978). An adjacent pool and riffle is described as a pool-riffle sequence. The features tend to remain in a relatively fixed position longitudinally instead of migrating downstream like sand bars (Leopold et al., 1964). They are found both in alluvial and bedrock channels, but are most prevalent in gravel-bed channels (Leopold et al., 1964). They occur in transitional reaches with regard to transport capacity and sediment supply, existing somewhere between supply limited and approximately equal sediment supply and transport capacity. The exact transport-supply relationship is dependent on the degree of bed material armouring and the frequency of bed-surface mobility (Montgomery & Buffington, 1997). The water surface slope is greater over riffles than pools at low flows, but as discharge increases the differences diminish until a nearly straight water surface is obtained (Leopold et al., 1964). Under high flow conditions friction slope increases over the pools and decreases over the riffles causing pools to be dug and riffles built up.

Pool-riffle sequences are found both in straight and meandering channels (Leopold et al., 1964). Pools are often associated with bends in meandering channels, and are often accompanied by adjacent point bars, which result in asymmetrical cross-sectional profiles; whereas riffles tend to have more symmetric cross-sectional profiles (Keller & Melhorn, 1978).
Forced pool-riffle morphologies are common in forested mountain drainage basins (Montgomery & Buffington, 1997). They occur when pools are forced by obstructions including large woody debris, boulders, and bedrock outcrops. Bedform spacing may be reduced from the typical 5 – 7 channel widths (Montgomery & Buffington, 1997). Obstructions are often added to a channel to force the formation of the features during restoration efforts that aim to create pool-riffle sequences (Newbury & Gabourey, 1993).

Pool-riffle morphologies are characteristic of channel reaches with gradients less than 0.015 (Montgomery & Buffington, 1997). Forced pool-riffle morphologies can occur in reaches with gradients as high as 0.03 where plane-bed reaches would typically be found (Montgomery & Buffington, 1997). Relative roughness is less than 0.3, and increases with reach slope within this range (Montgomery & Buffington, 1997).

1.1.2 Pool-Riffle Formation and Maintenance

Pool-riffle maintenance refers to the processes that maintain pool-riffle relief. Maintenance processes allow fine sediment deposited in pools during low flows to be removed from the pools at high flows. By the same token, in riffles, maintenance processes allow sediment to be scoured away and deposited at low and high flow respectively (Milan, 2013). Some maintenance processes can also explain the formation of bedforms, specifically those relating to scour and deposition, but others only explain self-maintenance of existing features. The seminal theory, velocity reversal hypothesis (Keller, 1971) (Section 1.1.2.1), has been debated for decades and alternative theories have been introduced, but scientific consensus has not been reached. Alternative theories are generally either based on multi-dimensional flow structures, sediment transport characteristics, or channel width variations.
1.1.2.1 Velocity Reversal Hypothesis

Gilbert (1914) was the first to introduce the idea that changing bed velocity is responsible for the scour of pools at high flows, and filling of pools at low flows, but was unable to collect measurements to quantify his theory. Keller (1971) expanded on this idea and was the first to present a formal hypothesis for the processes sorting fine material into deep pools, and coarse material onto shallow riffles. Keller proposed that mean near-bed velocities for a pool are lower than those for a riffle at low flows, and that pool velocities increase with discharge at a higher rate than do those over riffles. Higher tractive forces over riffles during low flows would result in much of the fine material transported over them being deposited in the pool. Keller was able to demonstrate convergence of pool and riffle near-bed velocities suggesting material transported through the riffle was also able to be transported through the pool; however, it could only be hypothesized that pool velocities would exceed riffle velocities at high flow, allowing the coarsest material transported through pools would be stored on riffles and bars, through extrapolation of the near-bed velocity data. The bed structuring that is destroyed by high flows is thought to be re-established during the falling limb of the flood.

Other workers have shown evidence of the near-bed velocity reversal hypothesis in their experiments (Jackson and Beschta, 1982; Robert, 1997), sometimes evaluating other hydraulic parameters for reversal or convergence including mean shear stress (Lisle, 1979), water surface slope (Lisle, 1979; Thompson et al., 1999), and section averaged velocity (Keller and Florsheim, 1993; Thompson et al., 1999). In some cases, reversals are only seen conditionally (e.g. Carling & Wood, 1994), suggesting that they may not be the primary maintenance mechanism for pool-riffle sequences. There are also a number of arguments against the hydraulic parameter reversal
theories (e.g. Sear, 1996). Several researchers have demonstrated that pools commonly have larger cross-sectional areas than riffles, so pools should have lower cross-sectional velocities to maintain flow continuity (Carling, 1991).

### 1.1.2.2 Flow and Turbulence Effects

When presenting his velocity reversal theory Keller (1971) assumed that the increased velocities in the pool during high flow resulted from flow convergence in the pool, which imparted a jetting force on the pool sediments. Flow divergence over the riffle then resulted in relatively low bottom velocities, causing deposition of entrained sediments. Following this postulation, a number of researchers have sought to explain pool-riffle maintenance using flow and turbulence effects.

MacWilliams et al. (2006) presented a hypothesis of flow convergence routing for pool-riffle maintenance. Using 2-D and 3-D hydrodynamic models validated using data from Keller’s original field site, they found evidence of flow parameter reversals, but found flow constrictions and convergence to be the dominant process for maintenance. They suggest that flow constriction causes flow convergence and acceleration at the pool head and creates a jet of flow through and downstream of the constriction that may not align with the deepest part of the pool. Shear stresses and velocities are maximized through this flow zone, allowing the coarsest sediments to be routed through or around the pool. Divergence at the pool tail and riffle head results in decreased velocities, and thus deposition. MacWilliams et al. (2006) reviewed a number of previous studies that evaluated the velocity reversal theory and the data from the studies either supported their new hypothesis, implied support, or did not discuss it. Sawyer et al. (2010) used digital elevation models of the large gravel-bed lower Yuba River, California, and 2-
D mechanistic modelling to confirm the occurrence of flow convergence routing as a method of pool-riffle maintenance in large rivers. The relationship between flow constrictions and convergence is unable to account for situations where pool-riffle sequences occur in reaches with relatively uniform width, preventing this theory from explaining all maintenance situations.

MacVicar and Roy (2007a) studied a forced riffle pool sequence, and found a near-bed velocity reversal to only occur between the riffle and pool tail, with near-bed velocity equalization occurring between the riffle and mid pool, and no equalization or reversal occurring between the riffle and pool head. Sediment entrainment through the thalweg was instead attributed to high turbulence intensities. There was also some support found for flow convergence routing, as bars had higher near-bed mean velocities, which could indicate sediment was being routed around the deepest part of the pool. They found horizontal shear layers to develop as the slope rapidly increased at the pool head, and high intensities of turbulence were found in this area (MacVicar and Roy, 2007b).

Thompson and Wohl (2008) also studied velocity patterns in forced-pool and riffle units. They summarized the hydraulic patterns in forced pools, where the imposed constriction produces backwater, a local increase in water-surface slope, a flow jet through the centre of the pool, and a recirculating eddy in the wake of the constriction. A zone of free shear develops between the eddy and the jet, creating intense turbulence. The generation of the turbulence and subsequent decay is thought to play an important role in sediment transport. The changes in depth or width around these constrictions control flow acceleration and deceleration, which in turn impact turbulence generation. Turbulent bursts are significant enough flow structures that they can lead to sediment entrainment in conditions below the critical value of shear stress due to
instantaneous pressure differentials. Turbulent vortices form in separation zones at pool heads, and decay as they travel downstream through the pool. The vortex decay is thought to result in the formation of boils through the pool exit slope, causing deposition in the area of laterally convergent flow over the exit slope and following riffle.

1.1.2.3 Sediment Dynamics

Booker et al. (2001) used computational fluid dynamics to model 3-D flow structures and patterns of shear stress based on field data from a natural riffle-pool sequence. They found that cross-sectional velocities and bed shear stress both decreased over riffles and increased in pools with increasing discharge, but the changes were not enough to inflict a flow parameter reversal. Instead, they found that the dominant maintenance mechanism was sediment routing as a result of flows passing over the downstream slope of riffles and into pool-heads, bypassing the centre of the pool. They rejected the theory of flow convergence eroding pool material, and instead suggested that sediment was routed to bypass pools.

Milan (2013) also presented a sediment routing hypothesis as an alternative to the velocity reversal hypothesis. He suggested that at bankfull flow, clasts are effectively routed around pools with riffles acting as pools would in the traditional models and bars as riffles, as the bars have the greatest elevation and tractive force at this stage. At high flows, clasts only entered pools by avalanching from point bars. These conclusions were drawn using a sediment tracer field study and computational fluid dynamics.

De Almeida and Rodríguez (2011) suggested that the knowledge gap relating to pool-riffle maintenance and morphodynamics could be solved by coupling flow and sediment dynamics. They found that sediment transport reversals occurred more frequently than shear stress or
velocity reversals, with a sediment transport reversal being defined as “the situation where transport in the pool is higher than in the downstream riffle”. This indicates that pool-riffle self-maintenance events occur more frequently than predicted by the velocity reversal theory. The relationship between transport reversals and shear stress reversals can differ based on longitudinal grain sorting, relating to the availability of fines in the pool, and differential sediment mobility. They also highlighted the interdependence of adjacent pool-riffle units in a sequence, as aggradation of a downstream riffle may inflect backwater conditions on an upstream unit. This increases both the probability and magnitude of velocity reversal in the upstream sequence, increasing the chances of deposition on that riffle and scour in the pool. Similarly, if erosion occurs on a downstream riffle, it is also more likely to occur on the upstream riffle. They also noted that the units are able to self-control the limits of riffle erosion and aggradation, as deposition on a riffle is inversely related to the probability of velocity reversal in that unit, limiting the amount of deposition that is likely to occur, with the opposite holding true for erosion.

A simple fractional transport model was used by de Almeida and Rodríguez (2012) to investigate the development of pool-riffle sequences from a flat, unsorted bed with variable width under both constant and variable flow regimes. They stated that, under one year of a variable flow regime, “riffle deposition and pool erosion with suppression of sorting occurred during high flows, followed by restorative riffle erosion and pool deposition during the falling limb of the hydrographs”. The longitudinal sorting generated by the model was similar to that found in natural channels. When the same model was run from a flat bed with ten years of constant flow, low flows reduced pool-riffle relief, and flows over a certain threshold increased the relief. The
constant flow regimes resulted in much less sediment sorting than was found in the natural channel. When a low flow regime was applied to pool-riffle sequences developed under variable conditions, pools were filled and riffles eroded, reducing relief. Sediment sorting was increased during low flows in this scenario in response to high shear stress gradients. The results of the constant flow regime models provide a very extreme example of how flow regulation strategies can impact pool-riffle morphology, but may serve as valuable knowledge when designing dam release schedules.

1.1.2.4 Width Variations

Nelson et al. (2015) performed experiments in a straight flume with sinusoidal width variations. Starting from a flat bed, pools developed in narrow areas and riffles in wide areas, with the location and relief remaining spatially and temporally persistent throughout. The locations and relief were found to be independent of sediment supply, with overall slope adjustment exhibiting as the primary response to changes in sediment supply. The experiments were conducted with several unnatural constraints. The banks were fixed and unerodible, the discharge was constant, and the sediment mixture only contained sand and fine gravel. The lack of fine material in the grain size distribution may have prevented pool filling, along with the fact that it was a constant flow experiment, as filling is thought to occur during the falling limb of the hydrograph. This indicates that the observed relief magnitude consistency may not occur in natural systems. The location consistency relating to the occurrence of these features in relation to expansions and contractions may, however, be a natural phenomenon, as it has been observed in field studies (Montgomery & Buffington, 1997; White et al., 2010). White et al. (2010) quantified planform and elevation change of an incising gravel-bed river using aerial photo sets and digital elevation
models to investigate whether the persistence of riffles and pools was related to valley width variation. Eight out of the ten riffle crests typically observed in each aerial image were determined to be persistent. Seven of the riffle crests were further studied, and it was found that they moved very short distances over two decades, despite instances of channel incision, lateral channel migration, and frequent floodplain inundation where associated flooding destroyed and reformed nonpersistent riffles. The persistent riffles were located near the widest part of the confining valley, and the deep pools near valley constrictions. The authors attributed the maintenance of these bedforms to the process of flow convergence routing. Numerical modelling done by de Almeida and Rodríguez (2012) also demonstrated the development of pool-riffle sequences from a flat bed, which then persisted over a year of variable flow conditions in locations strongly correlated with width variations.

1.1.2.5 Multi-Process Pool Formation

Thompson and Wohl (2008) completed an investigation of the dominant maintenance process in forced pools using field data, and proposed multi-process pool formation and maintenance where shifting amongst multiple relevant processes occurs over time and across systems. They found high velocities, high turbulence levels, maximum instantaneous velocities, and higher competence in pools. Relevant processes included jet flow, flow separation, vortex scour, and turbulence generation.

There is no general consensus on the most accurate theory of pool-riffle formation and maintenance, but it seems plausible that this could be due to process shifting, as suggested by Thompson and Wohl (2008). MacVicar and Roy (2007a) have noted that there is considerable variability between the morphologies of field sites used in pool-riffle studies, including bankfull
width, depth, slope, and grain size of both free-formed and forced reaches. This could explain the confusion between competing theories of maintenance, formation, and sediment sorting, as many processes have only been observed under certain conditions. Examples include the seminal theory of velocity reversal being suggested to hold true only in situations where the cross-sectional area of the pool is less than that of the riffle (Keller and Florsheim, 1993), and sediment routing’s inability to adequately explain pool formation, only maintenance (Thompson and Wohl, 2008).

1.1.3 Sedimentology

There has long been debate on the comparative sediment texture of pools and riffles. Most field observations of sediment texture are done at lower flows, which can add difficulty to the task of examining grain size distributions throughout the duration of a hydrograph.

Riffles are commonly thought of as being coarser than pools, especially at low flows, and a number of field studies have produced accordant results (e.g. Leopold et al., 1964; Keller, 1971; Richards, 1976; Sear, 1996; MacVicar and Roy, 2011). Some studies have observed larger particles in pools (Sear, 1996; Thompson et al., 1999), and others have found reaches with coarser riffles and reaches with coarser pools in the same river (Ashworth, 1987; Clifford, 1993). One study of pool-riffle systems where pools corresponded to channel width constrictions has found pool centres to be significantly coarser grained than the riffles and pool exit slopes, and increased pool D₅₀ (median grain size of the bed surface) to be correlated to narrower width constrictions (Thompson and Hoffman, 2001). Furthermore, some researchers have found no difference in sediment size between pools and riffles (Hack, 1957) or statistically insignificant differences (Richards, 1976; Milne, 1983). Numerical modelling of the formation of pools and
riffles associated with channel width contractions and expansions showed sediment sorting to be much stronger under variable flow conditions than under constant discharge, as textural differences decreased under high flow conditions, but could be re-established during the falling limb of a hydrograph (de Almeida and Rodríguez, 2012). It has long been hypothesized that fine material is deposited in pools during the falling limb of hydrographs (Keller, 1971). In addition to particle size, it has been suggested that packing density and relative protrusion differ between pools and riffles, with riffles having interacting and imbricate particle structuring, and pools open particle structuring (Clifford, 1993; Sear, 1996).

While general patterns have been observed where riffles are coarser than pools, a number of conflicting cases have been identified in the outlined studies. This suggests that there is still a need for further research to analyze relative changes in pool and riffle texture both spatially and temporally. More clarity on this issue may arise as our understanding of the processes that maintain these features is expanded.

1.1.4 Sediment Transport

Gravel tracer studies have been used since at least the first half of the twentieth century (e.g. Einstein, 1937) to study the entrainment and dispersal of sediment in rivers. They have emerged as an important field tool for studying sediment transport processes relating to pool-riffle sequences. Information can be gathered relating to transport distances, mobility, and both entrainment and disentrainment locations, which all contribute to the understanding of form-process interactions.
Published studies on tracers in pool-riffle systems have produced inconsistent results relating to relative transport distances. Studies involving tracer data from a range of pool-riffle channels have observed higher mean transport distances for a given value of excess stream power for particles originating on pools (Sear, 1996; Hassan and Bradley, 2017) and over floods (Thompson and Wohl, 2008), but other researchers have found higher mean travel distances for tracers originating in riffle reaches over long timescales (Papangelakis and Hassan, 2016). Other tracer studies have not produced conclusive results on relative transport distances of particles entrained from riffles and pools, but have demonstrated entrainment and deposition to be a function of morphology due to trapping of tracers on riffles and deposition on point bars (MacVicar et al., 2015).

Some studies relating to transport distance have focused on the impact morphological features have on deposition. For example, Milan et al. (2002) observed coarse clasts to move from riffle to riffle at flows near bankfull, and bar to bar at flows above bankfull level with transport distances exceeding one pool-riffle unit.

More consistent results have been found between studies relating to particle mobility, specifically referring to the portion of the bed or percentage of particles that are entrained.

Studies have demonstrated higher percentages of tracers and larger particles being mobilized from pools than riffles (Thompson and Wohl, 2008), full mobility in pool centres and exit slopes, but partial mobility over pool entrance slopes (MacVicar and Roy, 2011), lower critical thresholds of transport for particles initiating in pools (Sear, 1996), and more rapid increases in the portion of the pool under full mobility with increasing total excess flow energy expenditure than the riffle (Papangelakis and Hassan, 2016).
These studies all have relatively consistent findings, demonstrating either higher mobility in pools, or a faster increase in pool sediment mobility with flow rate. This is to be expected based on most of the pool-riffle maintenance theories introduced, including both velocity reversal and flow convergence.

1.2 Study Objectives

Formation and maintenance processes are the point of disagreement that has been most thoroughly studied in the literature; however, there are still many questions relating to sediment transport processes, hydraulics, and sedimentology surrounding the formation and maintenance of pool-riffle sequences. There are strong connections between all of these topics, as process and form both significantly influence the other, so individual discrepancies may not be resolved until it can be understood how the system functions as a whole.

It can be difficult to collect high resolution pool-riffle field data and isolate the key influences causing channel change, especially at high flows which may play the largest role in the development of channel morphology. Additionally, changes made during high flow events are often studied after a flood has passed, adding the difficulty of separating the effects of each hydrograph limb. To circumvent these issues, a controlled flume experiment was designed and executed to observe the formation of a pool-riffle sequence in a variable and non-erodible width, mobile gravel bed flume, and the subsequent response of the conditioned bed to increased flow conditions. The experiments were conducted using a physical model so that data could be collected in a controlled condition under a range of flows. Pool-riffle formation was studied at a flow approximately equal to the scaled bankfull discharge of East Creek, as bankfull discharge is considered by many to be the channel shaping flow.
The main goal of the experiment was to study the formation, adjustment, and maintenance of pool-riffle morphology in gravel bed rivers at the unit scale, focusing on sediment transport processes, sedimentology, and hydraulics.

The main research questions addressed during the experiment are:

1. What are the main adjustment parameters when a pool riffle sequence:
   a. Is formed from a well-mixed bed with uniform slope and fixed, non-erodible walls under bankfull flow conditions.
   b. Adjusts in response to increased discharges.

2. Do textural differences emerge between pools and riffles developed under flows above bankfull?

3. How does sediment mobility differ between pools and riffles at flows above bankfull?

4. Will hydraulic parameter reversals occur in a controlled flume environment modelling a channel reach characterized by width constrictions?
Chapter 2: Data Collection and Analysis

2.1 Experimental Design

2.1.1 Flume Design

Flume experiments were conducted at the BioGeoMorphic eXperimental Laboratory (BGMX Lab) at the University of British Columbia, Vancouver, Canada. The experiments were conducted in an 18 m long flume (15 m experimental length) with a width of 1 m, that was then modified to produce non-uniform width changes by installing rough-faced veneer-grade D plywood sidewalls. The current flume configuration was designed by Shawn Chartrand for his PhD thesis (Chartrand, 2017) as a physical model of a riffle-pool reach of East Creek, a small mountain stream located in the University of British Columbia's Malcolm Knapp Research Forest in British Columbia, Canada (Figure 2.1). Relevant model parameters have been summarized in Table 2.1.

A geometric scale field: model ratio of 5 was determined based on Henderson (1966), and used to determine experimental channel widths and the experimental grain size. Both weak and strong channel expansions and contractions were modelled. Symmetrical banks were constructed in the flume to simplify the geometry. The downstream most 1 m of the flume has a constant width to control the manner in which water and sediment exit the flume. The bed elevation is fixed at the outlet. No control was exerted on the water surface elevation at the outlet.

Water is introduced to the flume through a series of stacked plastic pipes that are 1 m long and 5 cm in diameter. The pipe lengths are approximately twice the average channel width, and flow is routed through them from the water holding tank into the flume to establish initially uniform
flow. A pump is used to recirculate the water only. The flow rate of the flume is controlled by adjusting the pump frequency from a control panel.

Figure 2.1 (a) Experimental flume, looking upstream from approximately 5.5 m. (b) East Creek, Vancouver, British Columbia, looking downstream.

Sediment was introduced at the upstream end of the flume using a sediment conveyor that operated at a constant, known velocity, allowing for the introduction of sediment at a specified feed rate. Sediment fell from the conveyor into a wooden grain randomizer where cross-bars interrupt the movement of sediment into the flow, instead redirecting particles with random trajectories across the entire channel width. The sediment used as feed material was sourced from the same mixture as the sediment used to build the initial bed (Figure 2.2). The initial bed
was built to a thickness of 21 cm throughout to provide adequate material for the development of topography and to prevent erosion and scour from reaching the flume bottom.

Table 2.1 East Creek channel parameters and corresponding experimental flume parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>East Creek</th>
<th>Experimental flume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental reach length (m)</td>
<td>75</td>
<td>15</td>
</tr>
<tr>
<td>Bed slope (m/m)</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Channel width (m)</td>
<td>2.40-4.10</td>
<td>0.37-0.78</td>
</tr>
<tr>
<td>Bankfull flow (m$^3$/s)</td>
<td>2.3 - 2.5</td>
<td>0.042</td>
</tr>
<tr>
<td>Bed surface grain size distribution (mm)</td>
<td>0.5 – 128</td>
<td>0.5 – 32</td>
</tr>
<tr>
<td>Bed surface D$_{50}$ (mm)</td>
<td>38</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Figure 2.2 Grain size distribution of sediment in initial bed mixture, used also as sediment feed.
When water and sediment reach the flume outlet they are directed over a light table that records images of the particles at a frequency of approximately 22 Hz, allowing for real-time computations of fractional sediment transport rates. The flow is then directed into a wire mesh basket to capture the sediment, and the water is recirculated back into the flume.

The flume is outfitted with a cart on a track that runs the length of the flume. Movement of the cart is remotely controlled using ACR-View software. The cart was installed to facilitate the collection of images and measurements along the length of the flume at a controlled velocity.

### 2.1.2 Experimental Discharge

The water supply discharge rates were based on Froude scaling, using a field to model Froude number ratio of 1. An experimental bankfull discharge of 42 L/s was scaled from an observed channel bankfull discharge of 2.3 to 2.5 m$^3$/s. The experimental bankfull discharge was adopted as the minimum experimental discharge, and additional discharges of 1.2, 1.7, and 2.1 times the bankfull discharge were also used, with the exact values chosen to allow the opportunity for comparison with previous experiments done using the current flume configuration. The entire grain size distribution was believed to be mobile for the experimental range of flows, as the average bed shear stress was calculated to be greater than the reference critical mobility stress for the median grain size of the bed surface during previous modelling.

### 2.1.3 Sediment Feed Rate

The sediment feed rate was estimated as an approximate of the sediment transport capacity rate by calculating the spatially-averaged capacity transport of the Wong and Parker corrected Meyer-Peter and Müeller function (Wong and Parker, 2006) and the mixed grain size Wilcock-
Crowe function (Wilcock and Crowe, 2003) (Table 2.2). This method may have resulted in a slight underestimation of sediment capacity for the higher discharge levels, due to increased discrepancies between the spatial average and true transport capacity as discharge increases.

Table 2.2 Sediment feed rates estimated to approximate sediment transport capacity.

<table>
<thead>
<tr>
<th>Water discharge rate (L/s)</th>
<th>Sediment feed rate (kg/min)</th>
<th>Stage duration (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>0.50</td>
<td>40</td>
</tr>
<tr>
<td>50</td>
<td>0.65</td>
<td>4</td>
</tr>
<tr>
<td>70</td>
<td>0.90</td>
<td>4</td>
</tr>
<tr>
<td>90</td>
<td>1.1</td>
<td>4</td>
</tr>
</tbody>
</table>

2.2 Experimental Procedure

The experiments began from a flat bed with a uniform slope that had been well-mixed to produce a random size distribution. The bed was not remixed or altered in between flow stages. Water supply discharge was held constant at the experimental bankfull discharge (42 L/s) for the first stage. The run continued until an equilibrium sediment transport condition had been achieved, resulting in an experimental stage duration of 40 hours. The equilibrium condition was assumed to occur when mass equilibrium was achieved between the sediment flux at the flume outlet and the sediment feed at the flume inlet. The water discharge rate was then increased for the three following stages to 50 L/s, 70 L/s, and 90 L/s, and each stage had a duration of four hours.

The 42 L/s stage was broken into observation intervals with durations that followed a geometric time sequence to capture rapid changes occurring in response to the initial flow perturbation. The intervals were intended to be 0.25, 0.5, 1, 2, and 4 hours long; however, the first interval was extended to a duration of 19 minutes, as this was the minimum time required to collect the
relevant data. After the geometric sequence reached 4 hours, all additional observation intervals were 4 hours in length. The increased discharge stages were each 4 hours long, so they were each treated as one individual observation interval.

The flow was turned off at the end of each observation interval to collect bed surface data. When the flow was restarted it was gradually ramped up over a period of four to five minutes to avoid disturbing the bed surface. The sediment feed and experimental time clock were restarted when the flow was high enough to induce sediment mobility. Every hour, beginning 290 minutes into the experiment, the flow was reduced to a flow rate at which sediment was not mobile, for additional photography of the bed. The flow was also reduced to this rate if the basket collecting sediment at the outlet of the flume reached capacity and needed to be replaced.

2.3 Data Collection

Composite bed surface photographs and digital elevation models were collected at the end of each observation period after the flow had been stopped. All other data was collected hourly beginning 4 hours into the experiment or earlier. A sample data collection schedule for one 4-hour observation period is found in Appendix A.

Flume stationing used for data collection and analysis was measured as distance from the flume outlet.

Data was collected relating to bed topography, sediment transport, sedimentology, and hydraulics. Some data relating to each of those topics was collected throughout the length of the flume or at the outlet of the flume to characterize the reach; however, certain data collection methods were only deployed through the central pool and riffle, and some data was collected
with a higher resolution through this area to better characterize the unit of interest. Other pools and riffles were identifiable throughout the experiment using the specified delineation method; however, the central sequence was chosen for monitoring due to its persistence in previous experiments, and distance from the flume boundaries. The monitored area of the pool and riffle is outlined in Figure 2.3.

![Figure 2.3 Flume width plotted from outlet to inlet (left to right). Station indicates distance upstream of flume outlet. Pitot tube locations are plotted. Areas of the central pool and riffle captured by acrylic boat photos and closely monitored are indicated.](image)

Bed and water surface profiles were collected throughout the length of the flume with higher spatial resolution through the monitored area. Fractional bedload transport rates and bedload texture were both measured continuously at the flume outlet and periodically through the monitored area. Photographs for characterization of bed surface texture were collected through the length of the flume and more frequently through the monitored area with higher image resolution. Near-bed velocity measurements were collected through the monitored area. Gravel tracers were deployed through the monitored area and at the upstream extent of the flume to
characterize particle mobility, focusing on how particle mobility is affected by the pool and riffle.

2.3.1 Topographic and Water Surface Data

2.3.1.1 Digital Elevation Models

High resolution topographic bed data was collected at the end of each observation period, after the flow had been stopped, using a camera and laser collection system. A green laser mounted to the flume cart projected a laser line perpendicular to the centreline of the flume, and a cart mounted camera captured the projected line. An image was collected every 2 mm. The data was then processed to create a digital elevation model of the flume bed.

2.3.1.2 Manual Profiles

Water surface profiles were collected manually during the first two observation periods, then hourly thereafter, 45 minutes into the hour. A manual profile of the bed surface elevations along the centreline of the flume was collected congruently with the water surface profile beginning 34 minutes into the experiment. Data was initially collected every 25 cm from the flume outlet to 15.75 m upstream. Beginning 270 minutes into the experiment, data sampling frequency was increased to a 10-cm interval from 7.0 to 10.0 m upstream of the outlet to increase the profile resolution through the monitored pool and riffle.

Both the DEMs and the manual bed elevation profiles were collected relative to the top of the flume, so the flume slope is not reflected in the raw bed surface elevation data.
2.3.2 Sediment Transport Data

2.3.2.1 Collection of Flux Material

Transported sediment was collected in a wire mesh basket at the outlet of the flume and weighed at the end of every observation interval or sooner if the basket reached capacity. All of the material collected over a four hour period was mixed and split to approximately 6 kg, then the split was dried and sieved. During the increased discharge stages, the material was mixed and split every two hours. The collected mass and grain size statistics were used to calibrate the LabVIEW code that processed the light table data.

2.3.2.2 Light Table

Sediment transport data was continuously collected at the outlet of the flume using a greyscale camera mounted over a light table that collected images at a frequency of 22 frames per second. LabVIEW code was used to process the images and compute fractional sediment flux rates for each second of the experiment. Accuracy of LabVIEW bedload transport outputs was verified by comparing the total mass of the analysis period to the dry mass of material collected at the outlet of the flume. If the total masses were not within 10% of each other input parameters including number of particles used for each bedload transport calculation, minimum particle size used for each bedload transport calculation, and darkness threshold for particle detection were adjusted and the LabVIEW code was rerun.

2.3.2.3 Bedload Samplers

Five modified miniature Helley-Smith samplers were constructed and used to sample bedload transport throughout the central pool and riffle. The samplers were deployed for five minutes
every hour beginning 250 minutes into the experiment at locations 7.72, 8.23, 8.72, 9.22, and 9.72 m upstream of the flume outlet. The samplers were offset 4.05 - 4.35 cm left or right of the flume centreline to avoid interference between adjacent samplers. Material collected in each sampler was then dried, sieved and weighed. Analysis of the bedload sampler data was not included in the scope of this research project.

2.3.3 Bed Surface Texture

Bed surface texture was measured indirectly through the use of image analysis.

2.3.3.1 Composite Photos

A composite photograph of the flume bed was collected at the end of each time step, after the flow was stopped. Photographs were taken using a camera mounted on the flume cart with 1 to 2 mm resolution. Composite photos were processed using a MATLAB code produced by Shawn Chartrand to create subsampled images for characterization of bed texture. The composite images were lined up longitudinally with a corresponding DEM, then were clipped to and overlain by the DEM. The DEM and composite photos were both subsampled to create 13-32x32 mm images, each with matching coordinates, taken every 1 m from 3 to 13 m upstream of the flume outlet. The matching DEMs could then be used to perform image coordinate mapping, assigning real world coordinates to the grains in the subsampled images which allows for uniform density of sampling grids.

2.3.3.2 Acrylic Boat Photos

Additional bed surface photography of the riffle and pool was taken at the end of each hour beginning 290 minutes into the experiment. The discharge was reduced to 16 L/s, below the
critical discharge for sediment transport, and an acrylic boat-like structure was lowered just below the water surface to smooth out the surface, reducing reflections that would impair the view of bed surface sediment. The flow was decreased before lowering the boat into the flow, as trials done at higher flow levels resulted in scouring of the bed due to flow pressurization. Photographs of the flume bed were taken through the acrylic boat using a downward facing camera mounted on the flume cart. Four photographs were taken of the monitored pool and riffle during each boat deployment. The photographs captured locations spanning 7522 – 8068, 8068 – 8614, 8614 – 9160, and 9160 – 9706 mm upstream of the flume outlet (Figure 2.3).

The acrylic boat was lowered onto the water surface using a rope and pulley system, so the location of the boat viewing window was apt to shift by a few centimetres between photos, but the area photographed by the camera was constant relative to the flume walls for the entire experiment.

2.3.4 Near-bed Velocities

A series of six pitot tubes were deployed every hour beginning 240 minutes into the experiment. The pitot tubes were deployed along the centreline of the channel with the tips located 7.69, 8.06, 8.44, 8.82, 9.18, and 9.59 m upstream of the flume outlet (Figure 2.3). Differential pressure measurements were taken at a frequency of 1 Hz for five minutes each time the pitot tubes were deployed. They were positioned to be parallel to the channel centreline and just above the channel bed, with the measurement ports approximated to be 0.5 cm above the bed; however, the contact points of the pitot tubes and the bed may have varied based on the direction and magnitude of the local bed slope, so the distance of the measurement ports from the bed may vary slightly. During the measurements of the fourth hour of the 70 L/s run and the second hour
of the 90 L/s run the pool was too deep for the second pitot tube to reach the bed, so these measurements were discarded.

At the end of the 70 L/s run the pitot tubes were used to collect velocity profiles at water discharge rates estimated to be below the critical value for sediment entrainment, including 20, 25, 30, and 35 L/s. Pitot tube measurements were taken at a frequency of 1 Hz for two minutes at each depth. Data was collected 0.5, 1.0, and 1.5 cm above the flume bed, 1.0 cm below the water surface, and at half the water depth. If the pitot tube was located in an area of very shallow flow a measurement was taken either 1.5 or 2.0 cm below the water surface instead at half the water depth to increase the proportion of the profile that was sampled. A bed surface manual profile was collected from 6.5 to 11 m upstream of the flume outlet for the 20 L/s and 35 L/s stages, and a manual water surface profile was collected from 6.5 to 11 m upstream of the flume outlet for each of the four stages. Measurements were collected every 10 cm along the flume centreline for each profile.

### 2.3.5 Particle Mobility

Several hundred particles from the two largest size classes of the experimental grain size distribution were sourced from the initial bed mixture, drilled, implanted with a radio frequency identification tag, and sealed with epoxy resin. The use of radio frequency identification tags allows for the tracking of individual grains, as they are each associated with a unique identification code, and allows for them to be located when they are buried in the subsurface without disturbing the bed. The stones were also painted with fluorescent colours to allow for visual identification of tracer located on the bed surface.
Tracers were deployed in the middle of the 42 L/s conditioning stage, and again close to the end of the 42 L/s, 50 L/s, 70 L/s, and 90 L/s stages to capture particle movements over a near-equilibrium bed (Table 2.3). 184 tracers were seeded in the first seeding event, and 160 tracers in every seeding event thereafter. An attempt was made to seed 40 tracers on the surface of the riffle, and 40 on the surface of the pool, but actual numbers differed slightly, as the features were not accurately delineated until after the experiments were completed. The combined 80 tracers were seeded over the monitored pool and riffle from approximately 7.5 – 10.0 m upstream of the flume outlet. The remainder of the tracers were seeded at the upstream end of the flume from approximately 15.00 – 16.65 m upstream of the flume outlet. The flow was stopped for each seeding event. The tracers were placed on top of bed within the specified longitudinal range and were evenly distributed longitudinally and transversely within the seeding section. Tracers were seeded more densely through the pool than the riffle in order to collect an equal number of data points in an area with significantly lesser width. After tracer seeding, the flow was restarted. The flow was stopped again when five of the seeded tracers were observed to be transported out of the flume, as once tracers are transported out of the system they cannot be used for analysis of transport distances, which may bias results towards lower virtual velocities. The tracers were then located either visually or using a handheld RFID antenna. The longitudinal and transverse location of each tracer was recorded along with the identification number read using the antenna, and whether it was buried or located on the surface. Tracers located on the surface were removed from the flume, but buried tracers were not removed to minimize bed disturbance. It took much longer for tracers to be transported out of the flume during the 42 L/s run, so tracer locations were recorded once without being removed, then were recorded and removed the second time.
that they were tracked to capture a secondary movement period. More detailed information on tracer seeding quantities and locations is found in Appendix B.

Table 2.3 Tracer seeding and tracking times.

<table>
<thead>
<tr>
<th>Water discharge rate (L/s)</th>
<th>Tracer seed time (minutes from beginning of stage)</th>
<th>Tracer track time (minutes from beginning of stage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>1670</td>
<td>1730, 1910</td>
</tr>
<tr>
<td>42</td>
<td>2330</td>
<td>2345, 2361</td>
</tr>
<tr>
<td>50</td>
<td>225</td>
<td>240</td>
</tr>
<tr>
<td>70</td>
<td>230</td>
<td>240</td>
</tr>
<tr>
<td>90</td>
<td>230</td>
<td>240</td>
</tr>
</tbody>
</table>

2.4 Data Analysis

2.4.1 Delineation of Pools and Riffles

The limits of the monitored pool were delineated using the manual bed elevation centreline profiles. Manual bed elevation profiles were chosen over the DEMs, as they were collected with a higher temporal frequency, and the pool/riffle boundary locations were needed for analysis of hourly data. A linear regression was performed on each profile with a set intercept of 181.04 mm in the DEM coordinate system to represent the fixed elevation of the flume outlet. The locations where the bed elevation profiles crossed the regression line were determined to be the upstream and downstream extents of the main pool. The main riffle begins at the upstream pool boundary. The bed surface profiles were collected relative to the top of the flume, and the flume slope was not used to retrend the profiles before conducting the analysis.
2.4.2 Sediment Transport Rates

2.4.2.1 Sediment Transport Calculations from Flux Material

Sediment that was transported out of the flume was captured in a wire mesh basket fixed at the outlet. The basket was emptied when it reached capacity, every four hours from the beginning of the experiment, at the end of each discharge stage, and two hours into each increased discharge stage. The wet mass of the collected sediment was measured each time the basket was emptied, and converted to dry mass by removing 3% as water weight, which was determined through previous testing. The basket capacity was approximately 125 kg of wet sediment. An average sediment mass flux was calculated using the masses from each basket change.

\[ \text{Sediment mass flux} = \frac{\text{Sediment wet mass} \times 0.97}{\text{Flux duration}} \]

All of the material collected throughout an observation interval was mixed and split to produce a representative sample of approximately 6 kg during the 42 L/s stage, and the collected sediment was mixed and split every 2 hours during increased discharge stages. The sample was then dried and sieved to generate a grain size distribution for the sediment flux of that time step.

2.4.2.2 Light Table Post-Processing

The light table did not function properly through the entirety of the experiments, especially in the last 20 hours of the 42 L/s stage. Images were not consistently captured at the target rate of 22 frames per second. The LabVIEW code interpolated results for the time steps that did not have the necessary number of images, and often produced illogically high bedload transport rates for these time steps, producing total computed masses that were as high as 300% of the mass collected at the outlet. From experiment hours 20 – 40 over 10% of the collected images were
not collected at the target frequency. An attempt was made to post-process the data and recover accurate trends. Data points that reported much higher masses for particular grain sizes than were found in corresponding light table images were deleted and replaced with moving averages. For data sets with the worst image capture rates, one minute moving averages were generated, and a correction multiplier was applied to match the total mass to that measured at the outlet. The data quality was too poor, and a decision was made not to use the light table data for the 42 L/s stage.

2.4.3 Grain Size Analysis

2.4.3.1 Composite Photos

A 100 point grid was plotted on each of the 13 subsampled images corresponding to a single composite photo. The grid density was selected to equate to the maximum grain size in the distribution to avoid resampling of grains. Once sampling grid points had been assigned to the images, the colour of the grain beneath each grid point was manually specified using a MATLAB code modified from one created by Shawn Chartrand. A characteristic grain size was assigned to each sampled grain based on the specified colour, allowing for the computation of grain size statistics. Computed grain size distribution statistics included the geometric standard deviation of the grain size distribution, the geometric mean grain size of the distribution, active layer thickness, $D_{10}$, $D_{16}$, $D_{50}$, $D_{84}$, $D_{90}$, and the sand fraction. Percentile statistics were calculated using:

$$D_{50} = \frac{S^- + (P - P^-)(S^+ - S^-)}{(P^+ - P^-)}$$
where S is the sediment class on the phi scale, P is the percent of sediment finer than that size class or the target percentile, and – and + indicate the lower bound and upper bound values enveloping the target percentile respectively. Grain size statistics are calculated as percent finer.

2.4.3.2 Acrylic Boat Photos

The maximum viewing area that was visible in all sets of photographs taken using the acrylic boat was determined for each of the four photo locations. Sampling grid coordinates were determined with a grid density of 203 pixels. The grid density of 203 pixels was selected as this would equate to 32 mm measured on the horizontal plane at the top of the flume walls, which is the maximum grain size in the distribution and will thus eliminate the possibility of resampling grains. Grid points were set with a consistent pixel density and pixel location for each photo in each experiment time set. The first grid point was plotted at the downstream extent of the maximum constant viewing window limits on the flume centreline, with additional points extending upstream and towards the flume walls until the maximum constant viewing window limits were reached. The upstream most column of grid points for the three downstream most photos were plotted at least 203 pixels from the photo extents to prevent resampling of the grain in the adjacent photo. This resulted in a 128 mm wide sampling window relative to the top of the flume, along the centreline of the flume. A total of 300 grid points were sampled for each photo set.

Although the pixel grid point density was constant, the grid point density in physical space changed spatially and temporally due to changes in the bed elevation, and thus pixels per grain, despite the fact that the photographs captured the same longitudinal area relative to the top of the flume each time.
Once sampling grid points had been assigned to the photos, the colour of the grain beneath each grid point was manually specified using a MATLAB code modified from one created by Shawn Chartrand. A characteristic grain size was assigned to each sampled grain based on the specified colour. Sampled grain sizes were attributed to either the pool or the riffle using the delineated pool/riffle boundary locations determined from the manual profiles. The number of sampling points through the pool and riffle varied from 105 – 175 and 125 – 195 respectively, dependent on the location of the pool/riffle boundary. Grain size distribution statistics could then be computed for both the pool and the riffle, using the same method as with the subsampled composite images.

2.4.4 Hydraulics

2.4.4.1 Water Surface Slope

The manual water surface and bed surface profiles were used to generate hydraulic inputs for shear stress calculations. Profile measurements were taken every 0.10 – 0.25 m from 1.00 – 15.75 m upstream of the flume outlet. The elevation data was extended to 0 m and 16.5 m upstream of the flume outlet using the slope of the flume. The elevation data density was then increased using linear interpolation between measurement points to generate elevation data points every 0.002 m. Some water surface profiles included standing waves, which result in negative water surface slopes causing issues with further hydraulic calculations. To eliminate negative water surface slopes, centred moving averages of the water surface elevations were calculated using the extended, interpolated water surface profile (Figure 2.4). The minimum averaging window that eliminated negative water surface slopes within the area of analysis
(acrylic boat extents) was chosen to maximize the preservation of the profile shape, meaning different sizes of averaging window were applied for each measured profile.

Figure 2.4 Example manual water surface elevation measurements and smoothed water surface elevation profile generated for hydraulic calculations.

Water surface slopes were calculated every 0.002 m from adjacent points in the water surface elevation smoothed profile.

Manual water and bed surface profiles were also collected during the 20, 25, 30, and 35 L/s discharges that were run to collect velocity profiles. The water surface slopes were not smoothed for these profiles, as an overall negative water surface slope was observed over the pool during the 20 L/s stage, so the method of smoothing the profile until no negative water surface slopes
remained could not be used. Water surface slopes were generated for these four discharges by plotting the water surface profile over the pool and riffle from the boat area limit to the delineated pool/riffle boundary, then generating a linear regression for each plotted area, and taking the slope of the regression as the water surface slope.

2.4.4.2 Section Averaged Velocity

Water depths were calculated every 0.002 m by subtracting the interpolated bed surface profile from the smoothed water surface profile. In doing so, an assumption is made that the centreline bed elevation is representative of that of the entire cross section. An average water depth value was generated for both the riffle and pool by averaging the water depth values from the relevant boundary of the photo limits of the acrylic boat, to the pool/riffle delineation boundary for that hour. Average flume width values were generated from the data within the same bounds. Both the depth and width data that was used for averaging had a longitudinal density of 2 mm. The boat photo limits were used as the upstream boundary of the riffle and the downstream boundary of the pool, as this is the area that was used to generate grain size statistics for the features, so the same area was used for all relevant parameter calculations for consistency.

A section averaged velocity was calculated for the pool and riffle every 1 – 2 hours using the flow continuity equation:

\[ U = \frac{Q}{BH} \]

where \( U \) is the section averaged velocity, \( Q \) is discharge, \( B \) is the average width for the section, and \( H \) is the average flow depth.

35
2.4.4.3 Section Averaged Bed Shear Stress

Section averaged bed shear stress values were calculated using the sidewall correction methods outlined by Vanoni and Brooks (Vanoni, 1975), and related equations presented by Wong and Parker (2006).

Hydraulic parameters were calculated for the pool and riffle using the average width, flow depth, and velocity values. Hydraulic perimeter was calculated from:

\[ P = B + 2H \]

followed by area of flow:

\[ A = BH \]

hydraulic radius:

\[ R_h = \frac{A}{P} \]

and Reynold’s number

\[ Re = \frac{4R_h U}{v} \]

A dimensionless friction coefficient was calculated according to the Darcy-Weisbach relation:

\[ f = \frac{8gSR_h}{U^2} \]

The roughness coefficient for the wall region \( f_w \) was calculated iteratively using the Newton-Raphson method to fulfill:
\[
\frac{Re}{f} = 10\left[\frac{1}{(2\sqrt{f_w})} + 0.40\right]^{1.5}
\]

which was presented by Wong and Parker (2006) for experiments with a smooth hydraulic boundary.

The roughness coefficient for the bed region was then computed using an equation derived from the water continuity equation and the Darcy-Weisbach relation

\[
f_b = f + \frac{2H}{B} (f - f_w)
\]

The hydraulic radii for each the wall and bed regions were calculated using the dimensionless friction coefficient equation.

The bed shear velocity was then calculated using:

\[
U_* = \sqrt{g R_h S}
\]

after which the bed shear stress shear stress could be calculated using:

\[
\tau_b = \rho U_*^2
\]

2.4.4.4 Near-bed Velocities

Near-bed velocities were calculated from pitot tube differential pressure readings using:

\[
v = \frac{2\Delta p}{\sqrt{\rho}}
\]

where \(\Delta p\) is the differential pressure measurement, and \(\rho\) is the fluid density.
Resulting velocities for each pitot tube were averaged over each five minute measurement period. Pool and riffle values were calculated by averaging the individual near-bed velocity values from the pitot tubes that were located downstream and upstream of the pool/riffle delineation boundary respectively for that hour. Negative differential pressure readings were not included in near-bed velocity calculations.

2.4.4.5 Boundary Shear Stress from Near-bed Velocities

Boundary shear stress can be calculated from near-bed velocity point measurements using the law of the wall.

Roughness height \( z_0 \), is first calculated using

\[
z_o = \frac{aD_p}{30}
\]

where \( a \) is 3 and \( p \) is 84 (Whiting & Dietrich, 1990). Shear velocity can then be calculated

\[
u_* = \frac{u\kappa}{\ln \left( \frac{z}{z_o} \right)}
\]

where \( u \) is near-bed velocity, \( \kappa \) is von Karman’s coefficient, taken to be 0.40, and \( z \) is measurement height above the bed. The measurement height above the bed was assumed to be 0.5 cm, although it likely varied slightly due to measurement error and effects of changes in bed slope magnitude and direction. Boundary shear stress can finally be calculated using:

\[
\tau_b = u_*^2 \rho
\]
2.4.5 Tracer Data

Virtual velocities and particle mobility fractions were calculated for each of the tracer tracking events. The data was filtered to remove any tracers that were seeded but not located.

When tracers were left in the flume for a second movement period instead of being removed after tracking, the tracked locations were considered to be the seed locations for the second movement period. Tracers that had not been removed during previous tracking events due to burial or not be located, may be included in secondary movement data if they were located during both the second “seeding” period and the secondary movement tracking period. Tracers are classified as having initiated on a riffle or in a pool for secondary movement periods based on their location at the beginning of the secondary movement period, not during the initial seeding.

2.4.5.1 Virtual Velocity

Virtual velocity was calculated for each particle using:

\[ \text{Virtual velocity} = \frac{\text{Station}_{\text{seeding}} - \text{Station}_{\text{recovery}}}{\text{Deployment duration}} \]

Tracers were classified as stationary if the difference between longitudinal stations of the seeding and recovery locations was less than 10 cm, which is within the range of error of the equipment. Stationary tracers and tracers that were transported out of the flume during the deployment period were not included in virtual velocity calculations.
2.4.5.2 Mobility

Particle mobility was calculated for each tracer deployment period as a ratio of the number of tracers that had moved further than the tolerance range to the number of tracers that were seeded. Tracers that were transported out of the flume during the deployment period were included in the count of mobile tracers, and tracers that were not located were not included in the count of tracers seeded.
Chapter 3: Results

3.1 Bed Evolution

3.1.1 Pool-Riffle Formation

The experiments began from a flat, well mixed bed, and the central pool and riffle formed within the first 19 minutes of the experiment, when the first DEM was obtained (Figure 3.1). The monitored pool and riffle, located at approximately the longitudinal midpoint of the flume (Figure 2.3), had lower and higher elevations than the initial profile, respectively.

Figure 3.1 Bed surface evolution through the first 12 hours of the 42 L/s stage. DEM centrelines are plotted and flume slope is detrended from profiles. Station is distance upstream of the flume outlet.

After the pool and riffle had formed, the entire bed aggraded at a spatially and temporally variable rate. Aggradation first began at the major channel expansion, approximately 10 m upstream of the flume outlet, and propagated upstream with time (Figure 3.2). After the
aggradation reached the upstream boundary of the flume, the entire length of the bed continued
to aggrade at a more spatially uniform rate, including the pool. Little change was seen in the
profile in the final 16 hours as the bed neared equilibrium conditions.

Figure 3.2 Bed surface evolution through the 42 L/s stage. DEM centrelines are plotted and flume slope is
detrended from profiles. Station is distance upstream of the flume outlet.

Within the first two hours more minor topographic undulations also formed within the upstream
most 4 m of the flume, with a wavelength of approximately 1 m and amplitude of approximately
2 cm. The undulation amplitudes lessen over time, but the features persist up until 8 hours into
the experiment, propagating to the downstream boundary of the riffle, then become less defined
at 12 hours.

Trended bed elevation profiles are found in Appendix C.
3.1.2 Pool-Riffle Adjustment

The equilibrium profile that was conditioned under a discharge of 42 L/s responded to increased discharges with spatially variable degradation (Figure 3.3). Degradation was generally lowest near the flume outlet, as this was a fixed elevation point. When the discharge was raised from 42 L/s to 50 L/s degradation was predominantly observed at the upstream end of the flume, and through the central riffle. When the discharge was increased to 70 L/s, high degradation occurred in the upstream most 6 m of the flume, with lower amounts occurring from approximately 4 to 10 m. When the discharge was further increased to 90 L/s, degradation primarily occurred in the central riffle, and the upstream most 2 m of the flume.

Figure 3.3 Bed surface profiles at the end of each stage. DEM centrelines are plotted and flume slope is detrended from profiles. Station is distance upstream of the flume outlet.
It is expected that adjustments would first occur at the flume inlet, where the effects of changing boundary conditions are first noticed, then propagate downstream.

### 3.1.3 Pool-Riffle Amplitude

The pool-riffle amplitude was calculated from the manual profiles taken every hour, beginning 94 minutes into the experiment (Figure 3.4). Amplitude values were calculated using manual elevation profiles that had the flume slope detrended from them to increase consistency in pool-riffle delineation and reduce the contribution of longitudinal distance to amplitude calculations. After the first 94 minutes, the pool-riffle amplitude generally fluctuated around an average value of 73 mm during the 42 L/s conditioning stage, but the amplitude was consistently below the average for the last 8 hours. The slope of the best-fit line of the amplitude over time is not significantly different from zero.

![Figure 3.4 Pool-riffle amplitude during the 42 L/s stage. Amplitudes are calculated from manual centreline bed elevation measurements where slope is detrended from the measurements. Average amplitude (73 mm) is plotted with a dashed line.](image)
When the discharge was increased to 50 L/s, the pool-riffle amplitude stayed relatively constant (Figure 3.5), fluctuating by only 3 mm, which is just higher than the measurement accuracy (1 mm). The highest amplitude value was 73 mm, which is equal to the average value of the 42 L/s stage. When the discharge was increased to 70 L/s the amplitude increased to a maximum value of 90 mm, and when the discharge was further increased to 90 L/s, the amplitude increased to a maximum value of 109 mm (Figure 3.5, Table 3.1).

Figure 3.5 Pool-riffle amplitude during increasing discharge stages. Amplitudes are calculated from manual centreline bed elevation measurements where slope is detrended from the measurements. Elapsed time is measured from the beginning of the 42 L/s stage of the experiment.
Table 3.1 Rate of change in pool-riffle amplitude and maximum pool-riffle amplitude for each increased discharge stage.

<table>
<thead>
<tr>
<th>Discharge (L/s)</th>
<th>Rate of pool-riffle amplitude change (mm/hr)</th>
<th>R²</th>
<th>Maximum pool-riffle amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>-0.1</td>
<td>0.0147</td>
<td>73</td>
</tr>
<tr>
<td>70</td>
<td>3.54</td>
<td>0.687</td>
<td>90</td>
</tr>
<tr>
<td>90</td>
<td>4.48</td>
<td>0.879</td>
<td>109</td>
</tr>
</tbody>
</table>

3.2 Sediment Transport

3.2.1 Pool-Riffle Formation

Due to equipment malfunction, the frequency of light table images was too low in the last 20 hours of the 42 L/s run to be able to post-process and calculate accurate sediment flux rates. Average flux rates were instead calculated every two to four hours when the sediment captured at the flume outlet was weighed.

The sediment flux rate at the flume outlet increased in the first 31 minutes of the 42 L/s stage as the central pool was being degraded and the degraded material was flushed from the flume. The sediment flux rate then decreased until 24 hours into the stage, as material was being stored in the bed and used to develop topography. After 24 hours, when adjustments to the bed profile became very minor, the flux rate began to increase (Figure 3.6) as increasing portions of the feed material were being transported over the bed instead of stored in it. At 37 hours, the average sediment flux rate surpasses the feed rate and then fluctuates slightly above the feed rate, indicating that that the criteria taken to signal equilibrium have been achieved.
Figure 3.6 Average sediment flux rate at the outlet of the flume during the 42 L/s run, normalized by the feed rate.

Absolute sediment flux rates are found in Appendix D.

The $D_{50}$ of the sediment flux at the flume outlet is lower than that of the mixture until approximately 25 hours into the 42 L/s stage, as fine material is being transported out of the flume during the development of the topography (Figure 3.7). The sediment flux coarsens after this point, as the bed profile is nearing equilibrium and the flux rate is nearing the feed rate again as more of the feed is being transported over the bed. The $D_{50}$ of the flux material decreases towards that of the feed near the end of the stage, but remains slightly coarser.

Flume and numerical experiments conducted by Ferrer-Boix and Hassan (2014) also produced results that showed oscillations in the grain size distribution of the sediment flux at the outlet of the flume in runs with coarse feed material, due to the transport of a coarse sediment wedge downstream through the flume affecting the availability of coarse material at the outlet.
3.2.2 Pool-Riffle Adjustment

Similar sediment flux responses were seen for each of the three discharge increases (Figure 3.8). There is an initial spike in the average sediment flux rate as the bed is degraded and material is transported out of the system. After the degradation has occurred, the flux rate decreases towards the feed rate again as the bed begins to approximate an equilibrium condition. The responses to increased discharge conditions occurred much more rapidly than the initial response of the flat bed to constant flow at approximately bankfull discharge. The absolute sediment flux rate was greatest during the 70 L/s stage (Table 3.2).
Figure 3.8 Average sediment flux rate at the flume outlet during increased flow runs, normalized by feed rate. Elapsed time is measured from the beginning of the 42 L/s stage of the experiment which reached equilibrium at 40 hours.

Table 3.2 Total mass flux and maximum average flux rates for each stage of the experiment. Average flux rates were calculated using masses of sediment collected at the flume outlet.

<table>
<thead>
<tr>
<th>Discharge (L/s)</th>
<th>Duration (hours)</th>
<th>Total sediment flux (kg)</th>
<th>Maximum average flux rate (kg/min)</th>
<th>Maximum normalized average flux rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>40</td>
<td>481</td>
<td>2.19</td>
<td>4.38</td>
</tr>
<tr>
<td>42</td>
<td>4 (last 4 hours of stage)</td>
<td>350</td>
<td>2.19</td>
<td>4.38</td>
</tr>
<tr>
<td>50</td>
<td>4</td>
<td>343</td>
<td>4.35</td>
<td>6.65</td>
</tr>
<tr>
<td>70</td>
<td>4</td>
<td>565</td>
<td>5.73</td>
<td>6.37</td>
</tr>
<tr>
<td>90</td>
<td>4</td>
<td>464</td>
<td>4.79</td>
<td>4.35</td>
</tr>
</tbody>
</table>
There were less image frequency issues with the light table during the increased discharge stages. Bedload flux rates were calculated every second, and a one minute centred moving average of the data is presented (Figure 3.9). Similar trends are seen as with the average flux rates calculated from collected bedload material, as expected.

**Figure 3.9** Sediment flux rate at the outlet of the flume during increased flow runs, normalized by feed rate. Data was collected using the light table and a centred one minute moving average is presented. Elapsed time is measured from the beginning of the 42 L/s stage of the experiment, which reached equilibrium at 40 hours.

Large fluctuations in the bedload transport rate, approximately around or below the feed rate, can be observed in the light table data. Similar results were previously reported by Ferrer-Boix and Hassan (2014) for flume and numerical experiments where the experiments with similarly coarse feed saw bedload transport rates trend towards the feed rate via an oscillatory path due to the
downstream movement of a coarse sediment wave influencing the availability of coarse material near the flume outlet.

The $D_{50}$ of the sediment flux at the flume outlet appears to be much more constant during the increased discharge stages (Figure 3.10), than during the conditioning under 42 L/s (Figure 3.7); however, grain size trends for the flux of each stage are only characterized by two measurements, so some smaller scale trends may be missed.

![Figure 3.10 Average median grain size of the sediment flux during the increased flow runs, normalized by the median grain size of the mixture. Elapsed time is measured from the beginning of the 42 L/s stage of the experiment, which reached equilibrium at 40 hours.](image)
3.3 Sediment Texture

3.3.1 Sediment Texture Throughout the Flume

After 19 minutes of continuous flow at 42 L/s a patch of fines formed around the riffle, just upstream of the pool/riffle boundary (Figure 3.11, Figure 3.12). The area upstream of this patch coarsens over the next 0.5 hours, and the fines propagate downstream. The upstream area and the area occupied by fines coarsen over the next three hours, after which a patch of coarse material originating from metres 11 to 13 propagates down the channel from hours 4 to 12 of the experiment. Absolute grain size values are presented in Appendix E.

Figure 3.11 Median bed surface grain sizes through the first 12 hours of the 42 L/s stage, normalized by the median grain size of the mixture. $D_{50}$ values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.
Figure 3.12 90\textsuperscript{th} percentile of bed surface grain sizes through the first 12 hours of the 42 L/s stage, normalized by the 90\textsuperscript{th} percentile grain size of the mixture. $D_{90}$ values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.

After the flow had been run continuously at 42 L/s for 0.3 hours high local variability was observed in the bed surface texture, as fine sediment was being entrained and settling throughout the flume (Figure 3.13, Figure 3.14). The entire length of the flume coarsened within the first 12 hours of flow, with relatively constant $D_{50}$ values from 8 m to 13 m. At 24 hours the coarse pulse was observed to have travelled to the downstream end of the channel, and the normalized $D_{50}$ fluctuated between a more consistent 1.1 to 1.5 from metres 4 to 13. As the channel neared equilibrium, the normalized $D_{50}$ fluctuated around 1.02 and 1.05 at 36 and 40 hours respectively, nearly approximating the initial sediment texture.
Figure 3.13 Median bed surface grain sizes through the 42 L/s stage, normalized by the median grain size of the mixture. $D_{50}$ values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.

Figure 3.14 90th percentile of bed surface grain sizes through the 42 L/s stage, normalized by the 90th percentile grain size of the mixture. $D_{90}$ values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.
When the flow was increased to 50 L/s, higher variability in the $D_{50}$ was observed throughout the flume at the end of the stage (Figure 3.15). At the end of the 70 L/s stage the $D_{50}$ variability lessened again, and fluctuated around a coarser normalized value of 1.3. The final texture of the 90 L/s stage mimics that of the 70 L/s stage, with some local adjustment. The mean flume $D_{90}$ significantly coarsens from the final 42 L/s bed to the final 50 L/s bed, and from the final 50 L/s bed to the final 90 L/s bed (based on paired two sample t-Test for means) (Figure 3.16). The mean $D_{50}$ significantly increased from the final 42 L/s bed to the final 70 L/s bed.

Figure 3.15 Median bed surface grain sizes at the end of each stage, normalized by the median grain size of the mixture. $D_{50}$ values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.
Figure 3.16 90th percentile of bed surface grain sizes at the end of each stage, normalized by the 90th percentile grain size of the mixture. D_{90} values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.

### 3.3.2 Sediment Texture of the Pool and Riffle

The pool and riffle both fine slightly over the first 38 hours of the 42 L/s conditioning stage, then coarsen slightly in the last 2 hours (Figure 3.17). A more immediate and consistent response to increased discharge is observed in the pool, with a decrease in D_{84} occurring in the first hour of the increased discharge stages, as the entrance slope is being used to store fine sediment. An overall coarsening of the pool and riffle is seen in response to increased discharge, with higher D_{84} values, but the response of the riffle is more smooth and consistent. Despite the slight differences observed, the principal result is that there is no significant difference between the means of the D_{16}, D_{50}, and D_{84} values of the pool and riffle for any stage of the experiment (Appendix E). Similar variability is seen between the grain size statistics of the pool and riffle.
and the data sets straddle each other. The $D_{16}$ and $D_{50}$ of the riffle are coarser than that of the pool at 8 hours, but this is the time when the coarse pulse is seen to be passing over the riffle in the full flume grain size analysis (Figure 3.11).

![Figure 3.17](image.png)

**Figure 3.17** 16th, 50th, and 84th percentiles of bed surface grain sizes for the pool and riffle.

### 3.4 Particle Mobility

#### 3.4.1 Virtual Velocities

When tracers were seeded part way through the 42 L/s stage at 28 hours, there was no significant difference between the virtual velocity of the particles initiating in the pool, and those initiating on the riffle (Figure 3.18). The initial movement observed in the hour following seeding had significantly higher virtual velocity than that in the subsequent two hours. When tracers were seeded one hour from the end of the stage, when the system was nearing equilibrium, virtual
velocities had a significantly higher mean (using only the one tail p-value for initial movement) and greater variance. Differences between the virtual velocities of tracers initiating in the pool and on the riffle were not significant in the movement observed in the first 15 minutes, but riffle particles had significantly higher (only by one-tail p-value) virtual velocities during the following 16 minutes. The virtual velocities of the secondary movement were higher, especially with the riffle tracers.

![Graph](image)

Figure 3.18 Virtual velocities of particles originating in the pool and on the riffle during the 42 L/s stage. The first survey represents the first time seeded tracers were tracked, but not removed. The second survey is the next time the same tracers were tracked. Error bars represent one standard deviation. Elapsed time is measured from the beginning of the 42 L/s stage of the experiment.

When examining virtual velocity response to increasing discharge, the initial tracer movement from hour 39 was used to represent the 42 L/s stage. This is because the tracking period is most similar to the conditions of the tracking periods at the increased discharge levels, being close to
the end of the stage and representing initial movement. There is no significant difference between the virtual velocity of particles initiating in the pool and riffle from 42 L/s to 70 L/s including between the discharge levels. There is a significant increase in virtual velocity when the discharge is increased to 90 L/s, and at this discharge the virtual velocities of particles initiating in the pool are significantly higher than those initiating in the riffle at (Figure 3.19).

![Virtual velocities of particles originating in the pool and on the riffle. Error bars are one standard deviation.](image)

**Figure 3.19 Virtual velocities of particles originating in the pool and on the riffle. Error bars are one standard deviation.**

### 3.4.2 Mobility

Particle mobility represents the percentage of particles that were set into motion. Although tracers that were transported out of the flume were not included in virtual velocity calculations, they were included when calculating mobility. During both the initial and secondary tracer movement periods in the 42 L/s conditioning stage, tracers seeded in the pool were more mobile than those seeded on the riffle (Figure 3.20). Mobility was also higher during initial tracer
movement periods than secondary tracer movement periods, particularly with tracers seeded on the riffle.

![Graph showing mobility of particles](image)

**Figure 3.20** Mobility of particles originating in the pool and on the riffle during the 42 L/s stage. The first survey represents the first time seeded tracers were tracked, but not removed. The second survey is the next time the same tracers were tracked. Elapsed time is measured from the beginning of the 42 L/s stage of the experiment.

A similar pattern was seen when the discharge was increased, with pool particles having higher mobility than riffle particles with the exception of the 70 L/s stage (Figure 3.21). The mobility of the riffle particles increases between the 42 L/s and 50 L/s stages, then becomes more constant at higher velocities.
Figure 3.21 Mobility of particles originating in the pool and on the riffle.

3.5 Hydraulics

3.5.1 Water Surface Slope

Water surface slopes were initially much higher over the riffle than the pool (Figure 3.22). Water surface slopes over the riffle continuously decreased with discharge, and water surface slopes over the pool increased with discharge until they converged at 42 L/s. At discharges above 42 L/s water surface slopes remained relatively constant with an average of 0.022 m/m over the pool, and 0.019 m/m over the riffle, both of which are greater than the flume slope (0.015 m/m). The pool slopes are slightly higher than the riffle slopes above 42 L/s, but the means from 42 L/s to 90 L/s are not statistically different (P-value = 0.15).
Figure 3.22 Average water surface slopes over the pool and riffle. Slopes of water surface elevation regression lines were used for 20-35 L/s values. Averages of 2 mm slope measurements were used for 42-90 L/s because the profiles were smoothed first. Linear regressions are plotted for 20 – 42 L/s and 42 – 90 L/s separately due to the break in the slope of the data points. Linear regression parameters are found in Table 3.3.

Table 3.3 Linear regression parameters for the water surface slope over the pool and riffle. The first set of regressions was fitted to the data collected at discharges from 20 – 42 L/s, and the second set was fitted to the data collected at discharges from 42 – 90 L/s, as an obvious break in the trends was observed at 42 L/s.

<table>
<thead>
<tr>
<th>Discharge (L/s)</th>
<th>Pool linear regression slope</th>
<th>Pool regression R²</th>
<th>Riffle linear regression slope</th>
<th>Riffle regression R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 – 42</td>
<td>0.0015</td>
<td>0.961</td>
<td>-0.0014</td>
<td>0.997</td>
</tr>
<tr>
<td>42 – 90</td>
<td>-0.00003</td>
<td>0.240</td>
<td>-0.0001</td>
<td>0.617</td>
</tr>
</tbody>
</table>
3.5.2 Section Averaged Calculations

Section averaged calculations were performed to generate average hydraulic values for the pool and riffle. The section averaged velocity is systematically higher through the pool than the riffle after 24 hours (Figure 3.23). The section averaged velocity through the riffle decreases slightly during the 42 L/s conditioning stage, but no significant trend is observed through the pool at this discharge. Section averaged velocity increases through the increased discharge stages. Values are more variable through the pool. Section averaged velocity increases at a higher rate through the riffle than the pool.

![Velocity Graph](image)

Figure 3.23 Section averaged velocity through the pool and riffle.

When looking at the data collected during the velocity profile measurements in conjunction with the section averaged velocity values averaged over each experiment stage, strong evidence of a section averaged velocity reversal is apparent. Power regression equations were determined for
the pool and riffle section averaged velocities (Figure 3.24). Using these power equations, the parameters converge at approximately 37 L/s and reverse at higher discharges.

Figure 3.24 Stage average section averaged velocities through pool and riffle. Pool regression equation is \( U = 0.2341Q^{0.3852} \) \((R^2 = 0.92)\). Riffle regression equation is \( U = 0.5188Q^{0.1648} \) \((R^2 = 0.86)\).

Bed shear stress was higher in the pool section than the riffle, with the exception of one measurement at 13 hours (Figure 3.25). Shear stress of the bed region increased slightly though the 42 L/s conditioning stage. There was an overall increasing trend in shear stress of the bed region when the discharge was increased, with shear stress in the pool region increasing at a higher rate.

A shear stress reversal occurs between the riffle and pool when the stage average values are plotted (Figure 3.26). The pool shear stress values increase rapidly with discharge until 70 L/s, after which the shear stress is relatively constant. Shear stress through the riffle was found to be relatively constant and independent of discharge.
Figure 3.25 Bed shear stress through the pool and riffle, calculated using section averaged hydraulic values.

Figure 3.26 Average shear stresses of the bed region through the pool and riffle for each stage. Bed shear stress values could not be calculated for the pool at the 20 or 25 L/s stages due to the presence of negative water surface slopes. Linear regression equation for the pool is $\tau = 0.552Q - 9.3657$ ($R^2 = 0.84$). Shear stress through the riffle is independent of discharge ($R^2 = 0.005$).
3.5.3 Near-bed Velocities

A series of six pitot tubes were placed just above the bed though the central pool and riffle. The near-bed velocities (Figure 3.27) were more variable than the section averaged velocities as the pitot tube measurements are influenced by local conditions. When the near-bed velocities are averaged over each discharge stage it appears that riffle near-bed velocities are higher at low flows then surpassed by pool velocities at higher flows, but differences between the power relations fit to the data sets are not statistically significant (Figure 3.28).

![Figure 3.27 Near-bed velocities calculated from pitot tube readings.](image)
Figure 3.28 Average near-bed velocities for each stage. Pool power regression equation is $v = 0.1321Q^{0.4253}$ ($R^2=0.85$). Riffle power regression equation is $v = 0.1805Q^{0.3453}$ ($R^2=0.69$).

Near-bed velocity values for individual pitot tubes are presented in Appendix G.

Negative pressure differential values were recorded by the pitot tubes with varying frequency throughout the experiments. The pitot tubes were deployed parallel to the channel walls, so the negative pressure differential readings can be interpreted as evidence of flow in a secondary direction. During the earlier hours of the pool-riffle formation negative differential pressure readings were most commonly measured near the riffle bed, but beginning at 24 hours the negative readings are generally more frequent over the pool bed (Figure 3.29). As the discharge increases, the amount of negative readings diminishes.
Figure 3.29 Percentage of pitot tube readings that returned negative pressure values, indicating flow that was not perpendicular to the channel centreline.

3.5.4 Pitot Tube Shear Stress Calculations

Boundary shear stress results are much more variable when calculated using near-bed velocities (Figure 3.30) than with section averaged hydraulic measurements. This is likely due to the effects of local conditions on near-bed pitot tube measurements. The effects of local conditions and the inability to measure the distance of the measurement port from the bed with high accuracy both contribute to variability of results, and could partially explain the discrepancy between the magnitude of near-bed velocity calculation results, and section averaged results.

Boundary shear stress decreases slightly though the 42 L/s conditioning stage, and there is no significant difference between the means of the pool and riffle data at this stage (p=0.42). There is an overall increasing trend with increased discharge but results are quite variable.
Figure 3.30 Boundary shear stress over the pool and riffle, calculated using measured near-bed velocities.

Data was also much more variable when looking for trends between the boundary shear stress data calculated from the near-bed velocities using law of the wall and discharge. As such, no evidence of velocity reversal was observed (Appendix F).

3.5.5 Velocity Profiles

Velocity profiles were plotted for each of the six pitot tubes (Figure 3.31). Water surface elevation profiles corresponding to each of the collection periods are plotted in Figure 3.32. The lowest velocities, and lowest change in velocity with depth were generally measured with pitot tube 1, which was located over the exit slope of the pool. This also corresponds to the location of greatest flow depth for all but the highest discharge. Pitot tubes four and five generally had the highest velocities and velocities that increased with depth at the fastest rate, other than the
highest discharge where there was more consistency between the six profiles. Pitot tubes four
and five were located over the riffle, near the pool/riffle boundary.
Figure 3.31 Velocity profiles collected using six pitot tubes at discharges of 20, 25, 30, and 35 L/s over a bed conditioned with a discharge of 70 L/s.
Figure 3.32 Water surface profiles during velocity profile measurements on a bed conditioned to 70 L/s. Locations of the six pitot tubes (PT) are indicated with dashed lines.
Chapter 4: Discussion

4.1 Pool-Riffle Sequence Formation

The central pool-riffle sequence developed around a major width constriction within the first 19 minutes of flow, and persisted in that location for the duration of the experiments. The pool was first formed through erosion of the bed below the initial elevation, and the riffle through aggradation above the initial bed elevation. Further elevation adjustments were made through spatially and temporally variable aggradation as the newly formed pool-riffle morphology moved towards equilibrium.

Bed aggradation was achieved through storage of incoming sediment supply, as is reflected in the low sediment flux rates during periods of elevation change, and increasing sediment flux rates as elevation changes slow in a near equilibrium bed, as a greater percentage of supply is transported over the bed.

Once the central riffle had formed through aggradation, the new higher bed elevation of the riffle imposed a new boundary condition for the flume area upstream of the riffle. The new boundary condition resulted in aggradation of the upstream section of the bed, with more or less parallel accumulation of sediment.

A coarse pulse developed at the upstream end of the flume, and travelled downstream through the channel from hours 4 to 24. The transport of the pulse out of the system is reflected in the spike in the median grain size of the sediment flux at the outlet, with a sharp rise beginning at 24 hours, and peaking at 29 hours.
4.2 Pool-Riffle Response to Flow Perturbations

The central pool-riffle sequences responded to increased discharge with temporally and spatially variable bed degradation, and increased pool-riffle amplitude. Some of the degradation with increased flow may be due to possibility of underestimation of transport capacity at these flows. Numerical modelling done by de Almeida and Rodríguez (2012) showed pool-riffle amplitude to increase with discharge when the features were developed under constant flow conditions, consistent with these results.

4.3 Sediment Sorting

No significant difference was seen in the 16th, 50th, or 84th percentiles of the pool and riffle throughout any stage of the experiment. This is consistent with results observed by Milne (1982) in a riffle-pool field study where he described riffles and pools as “a single coarser-grained sedimentary unit”. Similar results have also been reported from numerical modelling of the formation pools and riffles corresponding to locations of width contractions and expansions, which resulted in lower degrees of sorting when the features were developed under constant flow conditions than those developed under variable flow conditions (de Almeida and Rodríguez, 2012). Grain size sorting was initially observed in the numerical models, but dissipated as the more gradual response of topographic adjustment became dominant and riffle deposition and pool erosion decreased textural differences. Sediment sorting occurred on the falling limb of the hydrograph in variable flow models.

The first set of pool-riffle photos for grain size analysis were taken 290 minutes into the experiment, by which point significant topographic development had occurred, preventing
observation of initial grain size sorting had it occurred as described by de Almeida and Rodríguez (2012); however, composite images for analysis of grain size distribution throughout the flume were collected as early as 19 minutes into the experiment, and the $D_{50}$ was noticeably variable through the flume at this early stage. The use of the pool entrance slope for storage of fines immediately after discharge increases, and subsequent dissipation of pool-riffle textural differences could be hypothesized to be evidence of de Almeida and Rodríguez’s sorting trends.

It is difficult to identify high flow textural patterns in field studies when grain size distributions may be reflecting low flow sedimentsorting. Through the use of controlled flume experiments low flow sediment transport was negligible, which could explain why a finer pool did not result. The flume is a simplified model of nature, so it is possible that there are other mechanisms that lead to sediment sorting in nature that are not reproduced in the flume.

Particle structuring was not studied, which could have been an adjustment mechanism, as riffles have been thought to have tighter particle structuring (Clifford, 1993; Sear, 1996).

### 4.4 Particle Mobility

#### 4.4.1 Particle Mobility during Pool-Riffle Formation

Tracers seeded 28 hours into the 40 hour 42 L/s conditioning stage were more mobile than those seeded 39 hours in, but had lower and less variable virtual velocities. This could indicate that more supplied sediment is being stored in the bed earlier in the experiment than near equilibrium.

It is important to note that tracers seeded at 28 hours were located after 1 hour, whereas the tracers seeded at 39 hours were located after 0.25 hours, and the duration discrepancy could influence the results. Only one of the tracers seeded at 28 hours was transported out of the flume.
in the hour that they were deployed, whereas nine of the tracers seeded at 39 hours were transported out of the flume in the 0.25 hours that they were deployed, so the entire virtual velocity disparity is not likely attributable on deployment duration.

Pool particles were more mobile than riffle particles during all deployment periods, including the secondary movement periods where there is a lower chance of tracers being over loose, meaning the tracer particles are more likely to mimic the movement of those in the conditioned bed. This could be a process that contributes to the maintenance of the pool-riffle amplitude.

4.4.2 Particle Mobility during Periods of Increased Discharge

Tracers seeded near the end of the 42 L/s and 50 L/s stages were deployed for a duration of 15 minutes, and tracers seeded near the end of the 70 L/s and 90 L/s stages were deployed for a duration of 10 minutes. There is a chance that the discrepancy could cause a bias of higher virtual velocities for the 70 L/s and 90 L/s stages, despite the fact that there was no significant difference between the virtual velocities of the 42, 50, and 70 L/s stages; however, tracers were deployed for the same duration for 70 L/s and 90 L/s stages, indicating that the increase in virtual velocity is attributable to higher discharge.

4.4.3 Implications for Sediment Transport

Based on the trend of virtual velocity remaining constant until 90 L/s and then significantly increasing, and mobility increasing from 42 L/s to 50 L/s then staying constant or fluctuating, it can be hypothesized that initial increases in sediment transport rates above bankfull are initially due to more of the bed becoming mobile, and later due to mobile material travelling with higher virtual velocities. The absolute sediment flux rates at the flume outlet did not show a consistent
increase with discharge, but sediment flux rates through the pool and riffle specifically have not been analyzed.

**4.4.4 Differences in Pool and Riffle Particle Mobility**

Tracers seeded in the pool were consistently more mobile than tracers seeded on the riffle, with the exception of those deployed during the 70 L/s stage, when 55% of pool particles and 70% of riffle particles were mobile. It is not surprising that pool particles are more mobile, as near-bed velocities and section averaged velocities were generally higher in the pool. This phenomenon would likely be heightened if the pool had finer particles than the riffle, as has commonly been reported in the literature.

There was no significant difference in the virtual velocity of particles initiating in the pool and the riffle other than at 90 L/s, when the pool particles had higher virtual velocities, and during the secondary deployment near the end of the 42 L/s stage when the riffle particles had higher virtual velocities (using one tailed p-value).

**4.5 Hydraulics**

**4.5.1 Velocity Reversal Theory**

Very similar velocity reversal trends resulted (Figure 4.1, Figure 4.2) as were presented by Lisle (1979), who was also studying a channel with a mid-pool width constriction, and found the water surface slopes to converge at a discharge less than bankfull after which they were greater than or equal to the reach slope. The water surface slopes converged, and the slope over the pool was slightly higher at the highest velocity, but it was not statistically significant. The hydraulic radius
of the pool was higher than the riffle for all discharges in both studies, with the riffle values increasing at a faster rate, but there was a reversal of the best fit lines in this study.

![Hydraulic radii plot](image)

**Figure 4.1** Hydraulic radii of the pool and riffle, plotted to match the style of Lisle, 1979. Section averaged geometric and hydraulic values were used for calculations. Pool power regression equation is $R_h = 0.0156Q^{0.3959}$ ($R^2=0.98$). Riffle power regression equation is $R_h = 0.0045Q^{0.6755}$ ($R^2=0.99$).

The velocity profiles were all collected at flows below bankfull and at flows that were observed to be below the threshold for transport. At the lowest discharge levels, the velocities were highest over the riffle, as were the rates of change with depth, and the lowest velocities occurred in the pool. The profiles appeared to converge at the highest discharge level. This further contributes to the evidence of support for the velocity reversal theory.

Analysis of the bedload sampler data collected over the riffle and pool was outside of the scope of this study, so existence of a competence reversal could not be tested; however, competence reversal was not apparent from the bed texture, as there was no significant difference between
D$_{50}$ of the pool and riffle at any stage. The bed was not conditioned to equilibrium under any flow levels below bankfull, so it is possible that the appropriate data could not be captured.

Figure 4.2 Average water surface slope over pool and riffle plotted for comparison to Lisle (1979). Slopes of water surface elevation regression lines were used for 20-35 L/s values. Averages of 2 mm slope measurements were used for 42-90 L/s because the profiles were smoothed first. The average reach slope for each discharge based on a linear regression of the bed surface elevations is plotted for comparison.

Evidence of various hydraulic parameter reversals is summarized in Table 4.1.
Table 4.1 Evidence of hydraulics parameter reversals between the pool and riffle and the discharge level at which the pool and riffle data regression lines intersected.

<table>
<thead>
<tr>
<th>Reversal type</th>
<th>Evidence</th>
<th>$Q_{\text{reversal}}$ (L/s)</th>
<th>Regression type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water surface slope</td>
<td>Convergence</td>
<td>41.7</td>
<td>Linear</td>
</tr>
<tr>
<td>Section averaged velocity</td>
<td>Reversal</td>
<td>37.0</td>
<td>Power</td>
</tr>
<tr>
<td>Near-bed velocity</td>
<td>Reversal, not statistically significant</td>
<td>49.5</td>
<td>Power</td>
</tr>
<tr>
<td>Bed shear stress (section averaged)</td>
<td>Reversal</td>
<td>49.9</td>
<td>Linear</td>
</tr>
<tr>
<td>Bed shear stress (from law of the wall)</td>
<td>No evidence</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Competence</td>
<td>Not evaluated</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4.5.2 Secondary Flow

Negative pressure differential recordings may provide evidence of secondary flow patterns, although the direction of flow cannot be deduced. Previous studies have observed the generation of turbulent vortices at width constrictions, often related to flow separation over the pool entrance slope, which contribute to scour and particle entrainment through the center of the pool (Hassan and Woodsmith, 2004; MacVicar and Roy, 2007b; Thompson and Wohl, 2008).

MacWilliams et al. (2006) also observed secondary circulation to occur through a pool in model simulations, and the degree of secondary circulation increased with discharge. The high occurrence of secondary flows in the pool near equilibrium during the 42 L/s stage and at the
beginning of the 50 L/s stage could suggest that this is an important maintenance process; however, more data would need to be collected to conclusively deduce this. There is no current explanation for the higher occurrence of secondary flows over the riffle in the early stages of the experiment, or the lack of secondary flow measurements at the higher discharge levels, which contradicts the findings of MacWilliams et al. (2006). The latter could be due to changes in the size of the boundary layer preventing the capture of the secondary circulation through near-bed measurement, but there is no evidence to demonstrate this.

**4.6 Maintenance Mechanisms**

The results of this study can be applied to pool-riffle sequences that develop around channel width constrictions. Generated results can inform pool-riffle processes occurring under high flow conditions, which are difficult to study in the field. Major topographic change occurred very rapidly followed by more minor changes, with aggradation propagating upstream from the riffle, and a coarse sediment wave travelling downstream through the flume. Particle sorting was not a dominant response between the pool and riffle, especially near equilibrium, other than short-term fining of the pool as an immediate response to increased discharges; however, local fluctuations in sediment texture were observed near equilibrium when topographic changes had stabilized, which may indicate a very localized response. Higher section-averaged velocities, near-bed velocities, and water surface slopes were observed through the pool at high discharges, as well as higher virtual velocities through the pool at the highest velocity. The mobility of pool particles was also greater through the pool. All of these comparative parameters seem to support flow convergence theories, that the width constriction drives flow acceleration, increasing shear stresses and mobilizing sediment through the pool.
Chapter 5: Conclusion

An experiment was conducted in a variable, non-erodible width mobile-bed flume to study the formation, adjustment, and maintenance of pool-riffle sequences. A central pool-riffle sequence was rapidly generated around the strongest width constriction in the flume, and persisted for the duration of the experiment. Topographic, hydraulic, sedimentologic, and sediment transport data were collected to analyze how various parameters adjusted. The following were found:

1. A persistent pool-riffle sequence was generated around a channel width constriction where flow converges.
2. The pool-riffle sequence responded to increased discharges through
   a. Bed degradation, which may be due to sediment supply below capacity.
   b. Increased pool-riffle amplitude.
   c. Coarsening of the bed.
3. Sediment sorting between pools and riffles was not observed to occur at bankfull flow or higher flows.
4. Pool sediments are more mobile than riffle sediments, but only had higher virtual velocities at the highest discharge stage.
5. Hydraulic parameter convergences or reversals were observed between the pool and riffle with section-averaged velocity, water surface slope, and bed shear stress when calculated using section averaged velocities, but no evidence of competence reversal could be generated through analysis of bed texture.

The flume study produced valuable data relating to processes that shape pool-riffle sequences at high flows, which could be important for predicting the performance of pool-riffle sequences.
during flood conditions. Further study should include higher spatial resolution of velocity measurements to further investigate the occurrence of secondary flow patterns, and their importance in pool-riffle maintenance.

It would be useful to compare results to similar experiments where the bed was initially conditioned using lower flows, or followed by a long period of flow below bankfull to see if the classically described sediment sorting resulted between the pool and riffle.
References


Appendices

Appendix A  - Sample Data Collection Schedule

Table A.1 Sample data collection schedule for one four hour observation interval during the experiment.

<table>
<thead>
<tr>
<th>Experimental stage start time (min)</th>
<th>Duration (min)</th>
<th>Data collection event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>Flow is increased to experiment level. When flow surpasses critical value for sediment transport, experiment time clock, sediment feed, and light table data collection are started</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>Near-bed velocity measurements using pitot tubes</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>Bedload transport measurements using bedload samplers</td>
</tr>
<tr>
<td>45</td>
<td>12</td>
<td>Water and bed surface elevation profiles</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>Flow is lowered below critical value for sediment transport, acrylic boat is lowered into flow, and photos of the bed surface through the riffle and pool are taken</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>Flow is increased to experiment level. When flow surpasses critical value for sediment transport, experiment time clock, sediment feed, and light table data collection are started</td>
</tr>
<tr>
<td>70</td>
<td>5</td>
<td>Near-bed velocity measurements using pitot tubes</td>
</tr>
<tr>
<td>80</td>
<td>5</td>
<td>Bedload transport measurements using bedload samplers</td>
</tr>
<tr>
<td>105</td>
<td>12</td>
<td>Water and bed surface elevation profiles</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td>Flow is lowered below critical value for sediment transport, acrylic boat is lowered into flow, and photos of the bed surface through the riffle and pool are taken</td>
</tr>
<tr>
<td>Experimental stage start time (min)</td>
<td>Duration (min)</td>
<td>Data collection event</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>----------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td>Flow is lowered below critical value for sediment transport, acrylic boat is lowered into flow, and photos of the bed surface through the riffle and pool are taken</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td>Flow is increased to experiment level. When flow surpasses critical value for sediment transport experiment time clock, sediment feed, and light table data collection are started</td>
</tr>
<tr>
<td>130</td>
<td>5</td>
<td>Near-bed velocity measurements using pitot tubes</td>
</tr>
<tr>
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<td>Bedload transport measurements using bedload samplers</td>
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<tr>
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<td>12</td>
<td>Water and bed surface elevation profiles</td>
</tr>
<tr>
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<td></td>
<td>Flow is lowered below critical value for sediment transport, acrylic boat is lowered into flow, and photos of the bed surface through the riffle and pool are taken</td>
</tr>
<tr>
<td>180</td>
<td></td>
<td>Flow surpasses critical value for sediment transport Experiment time clock, sediment feed, and light table data collection started</td>
</tr>
<tr>
<td>190</td>
<td>5</td>
<td>Near-bed velocity measurements using pitot tubes</td>
</tr>
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<td>5</td>
<td>Bedload transport measurements using bedload samplers</td>
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<tr>
<td>225</td>
<td>12</td>
<td>Water and bed surface elevation profiles</td>
</tr>
<tr>
<td>240</td>
<td></td>
<td>Flow is lowered below critical value for sediment transport, acrylic boat is lowered into flow, and photos of the bed surface through the riffle and pool are taken</td>
</tr>
<tr>
<td>240</td>
<td></td>
<td>Flow is turned off. Composite photograph of the bed surface and digital elevation model are collected.</td>
</tr>
</tbody>
</table>
### Appendix B - Tracer Data

Table A.2 Parameters for tracers seeded through entire flume (upstream, pool, and riffle)

<table>
<thead>
<tr>
<th>Seed time</th>
<th>Recovery time</th>
<th>Movement type</th>
<th># seeded</th>
<th># in # missing</th>
<th># moved</th>
<th># stationary</th>
<th>Mobility</th>
<th>Mean virtual velocity</th>
<th>Median virtual velocity</th>
<th>Standard deviation virtual velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1670</td>
<td>1730</td>
<td>Initial</td>
<td>184</td>
<td>1</td>
<td>17</td>
<td>132</td>
<td>34</td>
<td>80%</td>
<td>0.046</td>
<td>0.026</td>
</tr>
<tr>
<td>1730</td>
<td>1910</td>
<td>Secondary</td>
<td>174</td>
<td>9</td>
<td>8</td>
<td>82</td>
<td>75</td>
<td>55%</td>
<td>0.0144</td>
<td>0.0122</td>
</tr>
<tr>
<td>2330</td>
<td>2345</td>
<td>Initial</td>
<td>160</td>
<td>9</td>
<td>2</td>
<td>75</td>
<td>74</td>
<td>53%</td>
<td>0.129</td>
<td>0.067</td>
</tr>
<tr>
<td>2345</td>
<td>2361</td>
<td>Secondary</td>
<td>162</td>
<td>6</td>
<td>2</td>
<td>75</td>
<td>79</td>
<td>51%</td>
<td>0.109</td>
<td>0.071</td>
</tr>
<tr>
<td>2615</td>
<td>2630</td>
<td>Initial</td>
<td>160</td>
<td>0</td>
<td>3</td>
<td>113</td>
<td>44</td>
<td>72%</td>
<td>0.084</td>
<td>0.040</td>
</tr>
<tr>
<td>2860</td>
<td>2870</td>
<td>Initial</td>
<td>160</td>
<td>1</td>
<td>2</td>
<td>108</td>
<td>49</td>
<td>69%</td>
<td>0.196</td>
<td>0.101</td>
</tr>
<tr>
<td>3100</td>
<td>3110</td>
<td>Initial</td>
<td>160</td>
<td>4</td>
<td>2</td>
<td>113</td>
<td>41</td>
<td>74%</td>
<td>0.315</td>
<td>0.254</td>
</tr>
</tbody>
</table>
Table A.3 Parameters for tracers seeded in pool

<table>
<thead>
<tr>
<th>Seed time</th>
<th>Recovery time</th>
<th>Movement type</th>
<th># seeded</th>
<th># in basket</th>
<th># missing</th>
<th># moved</th>
<th># stationary</th>
<th>Mobility</th>
<th>Mean virtual velocity</th>
<th>Median virtual velocity</th>
<th>Standard deviation virtual velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1670</td>
<td>1730</td>
<td>Initial</td>
<td>39</td>
<td>0</td>
<td>1</td>
<td>30</td>
<td>8</td>
<td>79%</td>
<td>0.044</td>
<td>0.039</td>
<td>0.037</td>
</tr>
<tr>
<td>1730</td>
<td>1910</td>
<td>Secondary</td>
<td>28</td>
<td>1</td>
<td>0</td>
<td>21</td>
<td>6</td>
<td>79%</td>
<td>0.014</td>
<td>0.014</td>
<td>0.010</td>
</tr>
<tr>
<td>2330</td>
<td>2345</td>
<td>Initial</td>
<td>42</td>
<td>3</td>
<td>0</td>
<td>18</td>
<td>21</td>
<td>50%</td>
<td>0.096</td>
<td>0.056</td>
<td>0.120</td>
</tr>
<tr>
<td>2345</td>
<td>2361</td>
<td>Secondary</td>
<td>38</td>
<td>1</td>
<td>0</td>
<td>19</td>
<td>18</td>
<td>53%</td>
<td>0.106</td>
<td>0.111</td>
<td>0.077</td>
</tr>
<tr>
<td>2615</td>
<td>2630</td>
<td>Initial</td>
<td>33</td>
<td>0</td>
<td>1</td>
<td>25</td>
<td>7</td>
<td>78%</td>
<td>0.124</td>
<td>0.099</td>
<td>0.113</td>
</tr>
<tr>
<td>2860</td>
<td>2870</td>
<td>Initial</td>
<td>40</td>
<td>0</td>
<td>2</td>
<td>21</td>
<td>17</td>
<td>55%</td>
<td>0.090</td>
<td>0.068</td>
<td>0.085</td>
</tr>
<tr>
<td>3100</td>
<td>3110</td>
<td>Initial</td>
<td>38</td>
<td>3</td>
<td>0</td>
<td>27</td>
<td>8</td>
<td>79%</td>
<td>0.363</td>
<td>0.428</td>
<td>0.191</td>
</tr>
</tbody>
</table>
Table A.4 Parameters for tracers seeded in riffle

<table>
<thead>
<tr>
<th>Seed time</th>
<th>Recovery time</th>
<th>Movement type</th>
<th># seeded</th>
<th># in basket</th>
<th># missing</th>
<th># moved</th>
<th># stationary</th>
<th>Mobility</th>
<th>Mean virtual velocity</th>
<th>Median virtual velocity</th>
<th>Standard deviation virtual velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1670</td>
<td>1730</td>
<td>Initial</td>
<td>45</td>
<td>0</td>
<td>5</td>
<td>23</td>
<td>17</td>
<td>58%</td>
<td>0.037</td>
<td>0.023</td>
<td>0.036</td>
</tr>
<tr>
<td>1730</td>
<td>1910</td>
<td>Secondary</td>
<td>45</td>
<td>3</td>
<td>2</td>
<td>17</td>
<td>23</td>
<td>47%</td>
<td>0.016</td>
<td>0.016</td>
<td>0.011</td>
</tr>
<tr>
<td>2330</td>
<td>2345</td>
<td>Initial</td>
<td>38</td>
<td>5</td>
<td>1</td>
<td>11</td>
<td>21</td>
<td>43%</td>
<td>0.122</td>
<td>0.084</td>
<td>0.135</td>
</tr>
<tr>
<td>2345</td>
<td>2361</td>
<td>Secondary</td>
<td>29</td>
<td>1</td>
<td>0</td>
<td>9</td>
<td>19</td>
<td>34%</td>
<td>0.172</td>
<td>0.184</td>
<td>0.101</td>
</tr>
<tr>
<td>2615</td>
<td>2630</td>
<td>Initial</td>
<td>47</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>17</td>
<td>64%</td>
<td>0.082</td>
<td>0.054</td>
<td>0.102</td>
</tr>
<tr>
<td>2860</td>
<td>2870</td>
<td>Initial</td>
<td>40</td>
<td>0</td>
<td>0</td>
<td>28</td>
<td>12</td>
<td>70%</td>
<td>0.104</td>
<td>0.067</td>
<td>0.086</td>
</tr>
<tr>
<td>3100</td>
<td>3110</td>
<td>Initial</td>
<td>42</td>
<td>0</td>
<td>1</td>
<td>29</td>
<td>12</td>
<td>71%</td>
<td>0.214</td>
<td>0.082</td>
<td>0.256</td>
</tr>
</tbody>
</table>
### Table A.5 Location of seeded tracers

<table>
<thead>
<tr>
<th>Seed time (min)</th>
<th>Minimum station (m)</th>
<th>Maximum station (m)</th>
<th>Minimum pool seed station (m)</th>
<th>Maximum pool seed station (m)</th>
<th>Minimum riffle seed station (m)</th>
<th>Maximum riffle seed station (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1670</td>
<td>7.630</td>
<td>15.650</td>
<td>7.63</td>
<td>8.55</td>
<td>8.63</td>
<td>10.20</td>
</tr>
<tr>
<td>1730</td>
<td>0.48</td>
<td>15.60</td>
<td>7.06</td>
<td>8.42</td>
<td>8.59</td>
<td>11.19</td>
</tr>
<tr>
<td>2330</td>
<td>7.55</td>
<td>15.63</td>
<td>7.55</td>
<td>8.68</td>
<td>8.75</td>
<td>10.05</td>
</tr>
<tr>
<td>2345</td>
<td>0.40</td>
<td>15.63</td>
<td>7.07</td>
<td>8.70</td>
<td>8.89</td>
<td>10.38</td>
</tr>
<tr>
<td>2615</td>
<td>7.63</td>
<td>15.65</td>
<td>7.63</td>
<td>8.37</td>
<td>8.40</td>
<td>10.08</td>
</tr>
<tr>
<td>2860</td>
<td>7.61</td>
<td>15.64</td>
<td>7.61</td>
<td>8.54</td>
<td>8.67</td>
<td>10.12</td>
</tr>
<tr>
<td>3100</td>
<td>7.51</td>
<td>15.64</td>
<td>7.51</td>
<td>8.43</td>
<td>8.50</td>
<td>10.16</td>
</tr>
</tbody>
</table>
Appendix C - Trended Bed Elevation Profiles

Figure A.1 Bed elevation profiles during 42 L/s stage with flume slope retrended. Station is the distance upstream from the flume outlet.

Figure A.2 Bed elevation profiles during increased discharge stages with flume slope retrended. Station is the distance upstream from the flume outlet.
Appendix D - Sediment Transport Data

Figure A.3 Average sediment flux rate at the flume outlet during the 42 L/s stage.

Figure A.4 $D_{50}$ measurements of sediment flux at the flume outlet during the 42 L/s stage.
Figure A.5 Average sediment flux rates at the flume outlet during increased discharge stages. Elapsed time is measured from the beginning of the 42 L/s stage of the experiment which reached equilibrium at 40 hours.

Figure A.6 D₅₀ measurements of sediment flux at the flume outlet during increased discharge stages. Elapsed time is measured from the beginning of the 42 L/s stage of the experiment which reached equilibrium at 40 hours.
Appendix E - Grain Size Distribution Plots

Figure A.7 $D_{50}$ measurements during the 42 L/s stage. $D_{50}$ values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.

Figure A.8 $D_{50}$ measurements during increased discharge stages. $D_{50}$ values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.
Figure A.9 $D_{90}$ measurements during 42 L/s stage. $D_{90}$ values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.

Figure A.10 $D_{90}$ measurements during increased discharge stages. $D_{90}$ values are derived from a 100 point 32 cm x 32 cm sampling grid. Station is the distance upstream from the flume outlet.
Table A.6 Two-tail p-values obtained from a paired two sample for means t-Test between grain size parameters of the pool and riffle.

<table>
<thead>
<tr>
<th>Experiment stage</th>
<th>D_{16}</th>
<th>D_{50}</th>
<th>D_{84}</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>All stages</td>
<td>0.71</td>
<td>0.54</td>
<td>0.72</td>
<td>35</td>
</tr>
<tr>
<td>42 L/s</td>
<td>0.93</td>
<td>0.40</td>
<td>0.64</td>
<td>24</td>
</tr>
<tr>
<td>50 L/s</td>
<td>0.30</td>
<td>0.38</td>
<td>0.28</td>
<td>4</td>
</tr>
<tr>
<td>70 L/s</td>
<td>0.91</td>
<td>0.94</td>
<td>0.81</td>
<td>4</td>
</tr>
<tr>
<td>90 L/s</td>
<td>0.71</td>
<td>0.59</td>
<td>0.16</td>
<td>3</td>
</tr>
</tbody>
</table>
Appendix F - Shear Stress Plots

Figure A.11 Boundary shear stress values calculated from near-bed pitot tube measurements.
Appendix G - Near-bed Velocity Data

Figure A.12 Near-bed velocities measured using pitot tube 1.

Figure A.13 Near-bed velocities measured using pitot tube 2.
Figure A.14 Near-bed velocities measured using pitot tube 3.

Figure A.15 Near-bed velocities measured using pitot tube 4.
Figure A.16 Near-bed velocities measured using pitot tube 5.

Figure A.17 Near-bed velocities measured using pitot tube 6.
Figure A.18 Percentage of differential pressure near-bed pitot tube readings that were negative through the pool and riffle at each discharge level.

Figure A.19 Percentage of differential pressure near-bed pitot tube readings that were negative for each pitot tube during velocity profile measurements.
Figure A.20 Percentage of pitot tube readings that returned negative pressure values for each pitot tube, indicating flow that was not perpendicular to the channel centreline.