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Bed particle displacement in a wandering gravel-bed river

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Abstract

The primary goal of this thesis was to investigate the influence of channel morphology on individual bed particle path lengths in a wandering gravel bed river, the San Juan River, BC. This was achieved through tracking the transport of sedimentary particles using PIT tags and also capturing changes in channel morphology through repeat topographic surveys over the same three year time period as the tracer tracking. Particle transport tended to remain within the riffle-pool-bar sequence in which they were seeded, with modal path lengths related to areas of deposition along bar margins, especially at the bar apex region. This aligned with overall changes observed in the channel, as bars appear to be migrating downstream and expanding laterally, causing erosion of the opposite bank. These findings point towards the link between overall channel morphodynamics and individual particle transport in bar-dominated gravel-bed rivers. Smaller tributaries, with plane beds, show a different pattern of particle movement.

KEYWORDS: PIT tags, RFID, gravel-bed rivers, wandering rivers, path length, morphology
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# Table of Contents

Abstract ......................................................................................................................................................... ii
Acknowledgements ......................................................................................................................................... iii
List of Figures ................................................................................................................................................. vii
List of Tables ................................................................................................................................................ x
List of Abbreviations and Symbols ............................................................................................................ xii
1. Introduction ................................................................................................................................................ 1
2. Background .................................................................................................................................................. 3
   2.1. Characteristics of Wandering Gravel-Bed Rivers ............................................................................. 3
   2.2. Particle Tracking ................................................................................................................................. 6
       2.2.1. Functional Relationships – Controls on Bed Particle Dynamics ............................................. 7
       2.2.2. Channel Morphology Relation with Bed Particle Dynamics ....................................................... 9
       2.2.3. Particle Tracking using Passive Integrated Transponders ....................................................... 10
   2.3. Geomorphic Change Detection ........................................................................................................... 12
       2.3.1. Active Layer Depth .................................................................................................................... 13
   2.4. Rationale for Research ....................................................................................................................... 13
3. Study Area .................................................................................................................................................. 16
   3.1. San Juan River .................................................................................................................................... 16
       3.1.1. Physiography .............................................................................................................................. 16
       3.1.2. Climate and Hydrology ............................................................................................................. 17
       3.1.3. Forest Harvesting and Restoration Work in the Watershed .................................................... 23
       3.1.4. Channel Morphology ................................................................................................................ 24
   3.2. Harris and Lens Creeks ....................................................................................................................... 32
4. Methods ..................................................................................................................................................... 33
   4.1. Tracer Experiment ............................................................................................................................... 33
       4.1.1. Tracer Stone Construction .......................................................................................................... 33
       4.1.2. Tracer Stone Deployment ........................................................................................................... 33
       4.1.3. Tracer Stone Recovery ............................................................................................................... 39
       4.1.4. Tracer Data Analysis .................................................................................................................. 42
   4.2. Geomorphic Change Detection ......................................................................................................... 45
       4.2.1. Data Description ........................................................................................................................ 45
5. Results and Interpretation .............................................................................................................. 51
  5.1. Tracer Recovery Rates .............................................................................................................. 51
  5.2. Path Length Distributions ........................................................................................................ 52
    5.2.1. Bar 6 .................................................................................................................................... 53
    5.2.2. Bar 7 .................................................................................................................................... 57
    5.2.3. Bar 15 ................................................................................................................................. 60
    5.2.4. Harris Creek ...................................................................................................................... 62
    5.2.5. Lens Creek ......................................................................................................................... 65
  5.3. Tracer Deposition by Morphological Unit ............................................................................... 67
  5.4. Effects of Discharge on Tracer Transport and Entrainment ....................................................... 68
    5.4.1. Critical Discharge Estimation .............................................................................................. 69
    5.4.2. Hydraulic Effects on Tracer Mobility .................................................................................. 73
    5.4.3. Hydraulic Effects on Tracer Path Lengths .......................................................................... 74
  5.5. Effects of Grain Size on Tracer Transport and Entrainment .................................................... 76
    5.5.1. Grain Size Effects on Tracer Mobility ................................................................................ 77
    5.5.2. Grain Size Effects on Tracer Path Lengths ....................................................................... 79
  5.6. Effects of Seeding Position on Tracer Transport and Entrainment .......................................... 82
  5.7. Active Layer Depth and Tracer Burial ....................................................................................... 86
  5.8. Geomorphic Change Detection Analysis ................................................................................. 89
    5.8.1. Bars 6 and 7 ....................................................................................................................... 90
    5.8.2. Bar 15 .................................................................................................................................. 95
    5.8.3. Harris Creek ...................................................................................................................... 97
    5.8.4. Lens Creek ....................................................................................................................... 99
    5.8.5. Active Layer Dimensions ............................................................................................... 100
    5.8.6. Summary of Geomorphic Change Detection ................................................................... 102
  5.9. Long-term Changes in Channel Morphology .......................................................................... 103
  5.10. Summary of Results .............................................................................................................. 105
6. Discussion .................................................................................................................................. 107
    6.1. Path Length Distributions ...................................................................................................... 107
      6.1.1. Significance of Individual Particle Transport over Longer Time-Scales ......................... 109
      6.1.2. Comparison of Particle Transport between the San Juan River and its Tributaries ....... 113
6.2. Hydraulic Forcing and Grain Size Effects on Particle Transport ......................................................... 113
  6.2.1. Hydraulic Forcing ............................................................................................................................ 114
  6.2.2. Grain Size .................................................................................................................................... 116
6.3. Tracer Recovery Rates ....................................................................................................................... 119
  6.3.1. Limitations on Recovery Rates and Recommendations for Future Field Campaigns .......... 121
6.4. Topographic Surveying ...................................................................................................................... 122
6.5. Tracer Burial and the Active Layer Depth ........................................................................................ 123
6.6. Implications for Restoration Work and Future Studies ................................................................. 124
7. Conclusion ........................................................................................................................................... 126
References ............................................................................................................................................... 127
Appendices ............................................................................................................................................. 136
  Appendix A LiDAR Specifications ........................................................................................................ 136
Curriculum Vitae .................................................................................................................................. 139
List of Figures

Figure 2.1: Alluvial channel classifications and governing processes based on Mollard, 1973 (from Church, 2006) ............................................................ 5

Figure 3.1: Location of the San Juan River Watershed .................................................................................................................. 16

Figure 3.2: Mean monthly precipitation and temperature at the Port Renfrew Climate Station .......... 17

Figure 3.3: Mean annual discharge at hydrometric station 08HA010 between 1960 and 2018 .......... 18

Figure 3.4: Mean monthly discharge at hydrometric station 08HA010 between 1959 and 2017 .......... 19

Figure 3.5: Mean monthly discharge by decade at hydrometric station 08HA010 between 1959 and 2017 .............................................................................. 19

Figure 3.6: San Juan River hydrograph from September 2015 to September 2018 ....................... 21

Figure 3.7: Hydrographs for the peak floods during each winter of the tracer experiment ........... 22

Figure 3.8: Planted willows on Bar 6 after < 1-year growth ........................................................................................................... 23

Figure 3.9: Bank erosion opposite Bar 15 ......................................................................................... 24

Figure 3.10: Changes in the San Juan River channel boundaries from 1995 – 2018 ...................... 27

Figure 3.11: Tail of Bar 5 with inner chute channel at low-flow ...................................................... 28

Figure 3.12: REM of the San Juan River from Fairy Lake to the Port San Juan inlet ....................... 29

Figure 3.13: REM of the San Juan River from the Harris Creek confluence to Fairy Lake ............ 30

Figure 3.14: REM of the San Juan River from the Bear Creek Main bridge to Lens Creek .......... 31

Figure 3.15: Location of the five tracer deployment study sites ...................................................... 32

Figure 4.1: Grain size distribution plots for the five tracer sites ...................................................... 35

Figure 4.2: Tracer launch lines for Bar 6 and Bar 7 ........................................................................... 38

Figure 4.3: PIT tag and the theoretical detection zone from Chapuis et al., 2014 ............................ 39

Figure 4.4: Biomark’s BP Plus Portable antenna and Antenna Cord System .................................. 40

Figure 4.5: Tracer stone burial ........................................................................................................ 42

Figure 4.6: Example of different measures of path length in a sinuous section of channel at Bars 6-7 ... 44

Figure 4.7: Comparison of methods used to measure path length – L ........................................... 44
Figure 4.8: Workflow for geomorphic change detection ................................................................. 47
Figure 5.1: Path length distribution for Bar 6 tracers .................................................................. 54
Figure 5.2: Tracer recovery locations for Bar 6 ......................................................................... 55
Figure 5.3: Planform view of the migrating bedload sheet at the apex of Bar 6 (from 2017) ........ 57
Figure 5.4: Path length distribution for Bar 7 tracers ................................................................. 58
Figure 5.5: Tracer recovery locations for Bar 7 ......................................................................... 59
Figure 5.6: Path length distribution for Bar 15 .......................................................................... 60
Figure 5.7: Tracer recovery locations for Bar 15 ...................................................................... 61
Figure 5.8: Path length distribution for Harris Creek tracers ...................................................... 63
Figure 5.9: Tracer recovery locations for Harris Creek .............................................................. 64
Figure 5.10: Path length distribution for Lens Creek tracers ...................................................... 65
Figure 5.11: Tracer recovery locations for Lens Creek .............................................................. 66
Figure 5.12: Tracer concentrations across morphologic units ................................................... 67
Figure 5.13: Time-lapse imagery of the apex of Bar 6 .................................................................. 71
Figure 5.14: Relationship between peak discharge and excess flow volume ............................... 72
Figure 5.15: Tracer mobility by year .......................................................................................... 74
Figure 5.16: Path length distributions for mainstem and tributary tracers recovered after exactly one year ................................................................................................................ 75
Figure 5.17: Grain size distributions of mobile, immobile, and unrecovered tracers ..................... 78
Figure 5.18: Tracer path lengths for each study site subdivided by grain size ............................... 81
Figure 5.19: Path length distributions subdivided by grain size for mainstem and tributary tracers recovered after exactly one year .................................................................................... 82
Figure 5.20: Bar 7 tracer launch line cross-sections, measured from 2015 and 2018 LiDAR-derived DEMs .......................................................................................................................................... 83
Figure 5.21: Tracer path lengths subdivided by initial seeding location ...................................... 85
Figure 5.22: Burial depths for each tracer grain size class .......................................................... 86
Figure 5.23: Distribution of tracer burial depths ....................................................................... 88
Figure 5.24: Comparison of DoDs for the Bar 6-7 reach, thresholded at the 80 and 95 % confidence intervals ................................................................................................................................................. 90
Figure 5.25: Bar 6 DoD and the position of buried tracers ................................................................. 93
Figure 5.26: Bar 7 DoD and the position of buried tracers ................................................................. 94
Figure 5.27: Bar 15 DoD and the position of buried tracers ............................................................. 96
Figure 5.28: Harris Creek DoD and the position of buried tracers ..................................................... 98
Figure 5.29: Lens Creek DoD and the position of buried tracers ....................................................... 99
Figure 5.30: Volumetric changes from DoDs as a function of changes in elevation ......................... 101
Figure 5.31: Changes in channel boundaries from 1995 to 2018, overlaid on top of 2015-2018 DoDs and
buried tracer positions .................................................................................................................. 104
Figure 6.1: REM of the Bars 6-7 reach of the San Juan River .......................................................... 112
Figure 6.2: Sediment calibre in the chute channel near the head of Bar 6 ........................................ 113
Figure 6.3: Mean scaled travel distance of tracers as a function of dimensionless unit stream power,
adapted from Vázquez-Tarrío et al., 2018 ..................................................................................... 115
Figure 6.4: Scaled travel distance of tracers as a function of scaled particle size, adapted from Hassan
and Bradley, 2017 ......................................................................................................................... 117
List of Tables

Table 3.1: Characteristics of gravel bars in the San Juan River ................................................................. 25
Table 4.1: Deployment dates of tracers by location ......................................................................................... 33
Table 4.2: Wentworth scale of grain size .......................................................................................................... 34
Table 4.3: Two input fuzzy inference system for elevation uncertainty ......................................................... 49
Table 4.4: Example membership function values (from Bar 15 FIS) ............................................................ 50
Table 4.5: Interpretation of types of change from image classification change detection .............................. 50
Table 5.1: Summary of tracer recovery rates by location and year ............................................................... 52
Table 5.2: Sensitivity analysis for average cross-section velocity calculations .............................................. 70
Table 5.3: Yearly summary of hydrologic variables ......................................................................................... 72
Table 5.4: Summary of floods exceeding 500 m$^3$/s over the tracer monitoring period .............................. 73
Table 5.5: Fraction of bed material represented by each tracer size class for each study site .................. 76
Table 5.6: Recovery rate for each tracer grain size class ................................................................................ 77
Table 5.7: Mobility of tracer grain size classes ................................................................................................ 78
Table 5.8: Recovery rates and relative mobility of Bar 6 tracer stones summarized by the morphologic unit in which they were initially seeded .................................................................................. 84
Table 5.9: Recovery rates and relative mobility of Bar 7 tracer stones summarized by the morphologic unit in which they were initially seeded .................................................................................. 84
Table 5.10: Recovery rates and relative mobility of Bar 15 tracer stones summarized by the morphologic unit in which they were initially seeded .............................................................................. 84
Table 5.11: Recovery rates and relative mobility of Harris Creek tracer stones summarized by the morphologic unit in which they were initially seeded .............................................................................. 84
Table 5.12: Tracer burial data summarized by location .................................................................................... 87
Table 5.13: Tracer burial data summarized by year .......................................................................................... 89
Table 5.14: Volumetric budget segregation results for the Bars 6-7 DoD ....................................................... 92
Table 5.15: Summary of tracer recovery rates within areas of erosion, deposition, or indeterminate change .................................................................................................................................................. 94
Table 5.16: Volumetric budget segregation results for the Bar 15 DoD .......................................................... 96
Table 5.17: Volumetric budget segregation results for the Harris Creek DoD ................................................. 98
Table 6.1: Synthesis of bedload transport studies using RFID tracer stones in rivers, adapted from Chapuis et al., 2015
List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM</td>
<td>digital elevation model</td>
</tr>
<tr>
<td>DoD</td>
<td>DEM of difference</td>
</tr>
<tr>
<td>FIS</td>
<td>fuzzy inference system</td>
</tr>
<tr>
<td>GCD</td>
<td>geomorphic change detection</td>
</tr>
<tr>
<td>GPS</td>
<td>global positioning system</td>
</tr>
<tr>
<td>LiDaR</td>
<td>light detection and ranging</td>
</tr>
<tr>
<td>PIT</td>
<td>passive integrated transponder</td>
</tr>
<tr>
<td>PPK GPS</td>
<td>post-processing kinematic GPS</td>
</tr>
<tr>
<td>REM</td>
<td>relative elevation model</td>
</tr>
<tr>
<td>RFID</td>
<td>radio frequency identification</td>
</tr>
<tr>
<td>RTK GPS</td>
<td>real-time kinematic GPS</td>
</tr>
<tr>
<td>TIN</td>
<td>triangulated irregular network</td>
</tr>
<tr>
<td>TLS</td>
<td>terrestrial laser scanner</td>
</tr>
<tr>
<td>UAV</td>
<td>unmanned aerial vehicle</td>
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List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
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<tbody>
<tr>
<td>A</td>
<td>watershed area</td>
<td>m²</td>
</tr>
<tr>
<td>b</td>
<td>channel width</td>
<td>m</td>
</tr>
<tr>
<td>Dₓ</td>
<td>grain size (of percentile x)</td>
<td>mm</td>
</tr>
<tr>
<td>g</td>
<td>acceleration due to gravity</td>
<td>m s⁻²</td>
</tr>
<tr>
<td>L</td>
<td>path length</td>
<td>m</td>
</tr>
<tr>
<td>ρ</td>
<td>density of water</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>Q</td>
<td>discharge</td>
<td>m³ s⁻¹</td>
</tr>
<tr>
<td>S</td>
<td>slope</td>
<td></td>
</tr>
<tr>
<td>δₓD₀D</td>
<td>propagated elevation uncertainty in DoD</td>
<td>m</td>
</tr>
<tr>
<td>V</td>
<td>flow volume</td>
<td>m³</td>
</tr>
<tr>
<td>ν</td>
<td>average cross-section velocity</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>ωₚ</td>
<td>peak unit stream power</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>ω*</td>
<td>dimensionless stream power</td>
<td>-</td>
</tr>
<tr>
<td>Z</td>
<td>elevation</td>
<td>m</td>
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Chapter 1: Introduction

The San Juan River is a wandering-style gravel-bed river on the west coast of Vancouver Island. Forestry activities during the latter half of the twentieth century in the San Juan River Watershed have been directly linked to increased landslide incidence and sediment delivery to the lower alluvial reach of the river, resulting in significant changes to the mainstem and tributary channel morphology (NHC Ltd., 1994). Over this period, the stocks of several salmonid species in the river declined (Burt and Palfrey, 2011). This motivated a restoration project in the watershed by the San Juan Stewardship Roundtable, with the overarching goal of improving and increasing physical habitat for fish in the river. As part of the planning and restoration work, a geomorphological assessment was undertaken by the BC Ministry of Forests, Lands, Natural Resources, and Rural Development (FLNRRD) to provide background on dynamics in the river, including the possible sediment sources and sinks in the alluvial reaches of the mainstem and tributaries. This requires knowing several things, but one is the bedload transport and bar dynamics, which will show the short-term behaviour of the river along with possible tributary sediment contributions. The fundamental problem is to assess bed particle movement and the possible connection to bar dynamics in the main channel.

Particle tracing has been developed in fluvial geomorphology as a method to assess bed material transport processes, especially where direct trapping is not possible, and to support general models of bed particle dynamics and the spatial pattern associated with morphologic development. One technique that has been used with increasing frequency in recent years, is tracking individual particles using passive integrated transponder (PIT) tags. This yields statistics on particle displacement under different flow conditions and for different particle sizes, from which bedload transport rates can be estimated, along with spatial patterns of particle displacement and size sorting. Most bedload tracking studies using PIT tags have been done on relatively small rivers with simple morphologies (Chapuis et al., 2015). There remains uncertainty as to the practicality of this method in larger rivers with active bar and bend development, where tracer particles may become deeply buried. Further questions arise as to whether the existing principles of bed particle dynamics and statistics of displacements, derived from smaller rivers, are applicable to channels with more complex morphology (Pynce and Ashmore, 2003a; 2005). Classically, hydraulic forcing has been viewed as the primary control on bed particle dynamics, and empirical or theoretical models are used to describe the frequency distributions for tracer path lengths. However, in more complex channels, such as the San Juan River, the idea that particle dynamics are to some extent tied to bar dynamics leads to
different expectations for the frequency distribution of particle path lengths, and the relative controls on those, compared with established knowledge and theory from smaller, simpler rivers.

Determining the characteristic particle path length(s) in a river is significant, because, when combined with the volume of sediment mobilized over a given time period, it provides an estimate of the bedload flux (Ashmore and Church, 1998; Church, 2006; Vericat et al., 2017). One idea, that has not been the focus of much of the bedload tracing literature to date, is that particle path lengths could be related to the scale and spacing of bars (Neill, 1987). If the scale and spacing of bars is an indication of typical particle path lengths, then we can simply use these measurements in calculations of the bedload flux. However, the veracity of this must first be demonstrated in the field, which can be achieved via particle tracing.

Therefore, the research in this thesis is governed by the following objectives:

1. Test the idea that particle path lengths are related to bar morphology and dynamics.
2. Determine the practical implications for particle tracing using PIT tags in a large river with complex bar morphology.
3. Evaluate differences in the sediment transport dynamics of the San Juan River and its major tributaries.
4. Explore the implications of results for management of the San Juan River and similar rivers.

Overall, these objectives were addressed through the use of PIT tag particle tracking over a three year period in the lower San Juan River and its two major tributaries, Harris and Lens Creeks. This was coupled with repeat topographic surveys before and after the tracer monitoring period, to reveal changes in channel morphology. More specific research questions are presented at the end of Chapter 2.
Chapter 2: Background

This chapter provides a review of our current understanding of bed particle dynamics and the interplay with channel morphology. This begins in Section 2.1 with a description of the relevant characteristics that define wandering-style rivers, such as the San Juan River. Following this, a summary of the key findings and results from particle tracking studies is presented in Section 2.2. The coupling of particle tracking with geomorphic change detection is outlined in Section 2.3. The rationale for this research, as built from the background material provided throughout the chapter, is presented in Section 2.4.

2.1 Characteristics of Wandering Gravel-Bed Rivers

Wandering rivers, such as the San Juan River, exist in piedmont landscapes and mountain valleys across the globe (Neill, 1973; Church, 1983; Fuller et al., 2003a; Burge, 2005; Church and Rice, 2009). The first mention of a wandering channel in the fluvial geomorphology literature was by Mollard (1973) in his airphoto classification of stream types, whereby he describes “shifting meanders in a stream with a ‘wandering habit’ ” (p. 347). While this channel type has been recognized for years, there has been relatively little focus on the processes and functioning of wandering channels, despite their propensity for providing diverse and complex physical habitat for various organisms (Buffington et al., 2003; Burge, 2004). As a result, the management and restoration of these rivers has become an issue.

Wandering channels are irregularly sinuous and can display aspects of both meandering and braided channels. While certain reaches may exhibit a single identifiable mainstem, it is also typical for wandering channels to display low-order braiding around islands and dissecting of bars at high-flows (Burge and Lapointe, 2005; Beechie et al., 2006). They are high-energy gravel-bed channels characterized by a moderate channel gradient, with complex bar development and some degree of lateral instability (Figure 2.1). Typically, the most common bar morphology is a lateral bar (i.e. a bar attached to one bank) and the dominant mode of deposition is lateral bar accretion (Desloges and Church, 1987; Rice et al., 2009).

Church and Rice (2009) describe a pattern of bar evolution whereby vertical growth is limited by the height at which sediment can be elevated, and the longitudinal growth of bars is limited by the length-scale of the channel (i.e. the distance between meanders), resulting in bars primarily growing laterally. This is accompanied by erosion of the opposite bank, producing a laterally unstable channel, and implies less systematic migration than true meandering channels (McLean et al., 1999; Fuller et al., 2003a). Hence the term ‘wandering channel’. Commonly bar growth is also coupled with the development of a secondary channel along the inside of the bar, which are termed chute channels (Charlton, 2008). These channels
transfer some fraction of the discharge and sediment load during floods but may be disconnected from the mainstem at the bar head during low flows (Rice et al., 2009).

McLean et al. (1999) have suggested that channel wandering is caused by sporadic movements of coarse bed material, or “transient gravel waves”, along the channel until they are incorporated into the bars, triggering bank erosion and lateral instability downstream. Bank erosion along more sinuous sections of channel results in downstream migration of bends. In the case of the San Juan River, NHC Ltd. (1994) reported increased sediment delivery to the lower reaches of the mainstem via headwater tributaries during the latter half of the twentieth century, also noting an increase in the total bar area and average width of the channel over this period. This could indicate that the increased sediment supply is responsible, at least in part, for maintaining the wandering morphology of the contemporary channel. This description of channel evolution has direct implications on particle tracking. If bars are primarily built out via lateral accretion in wandering channels, then particles must be preferentially transported to and deposited at bar margins. This relation between particle dynamics and the wandering-style channel evolution has not been explored in the bedload tracking literature to date. The results of bedload tracking in the San Juan River in this thesis will help to fill this gap in the literature.
Figure 2.1. Left: Alluvial channel classifications and governing processes based on Mollard, 1973 (sourced from Church, 2006). Right: Example of wandering channel morphology of the San Juan River.
2.2 Particle Tracking

In large rivers with complex morphology, the rate of bedload transport across the channel is variable due to elevation and roughness differences associated with the channel morphology. Therefore, traditional methods of collecting bedload transport data, such as in-channel samplers and traps, are of limited utility since they are installed at fixed locations and only sample part of the bed (Charlton, 2008). An alternative approach to directly collecting bedload, is to determine the movement of individual particles of different sizes in the channel using tracers (Hassan and Ergenzinger, 2005; Hassan and Roy, 2016; Hassan and Bradley, 2017). Tracer stones are individual grains, either natural or artificially made, that are identifiable and distinct from the native sediment in the river. Examples include particles that are composed of exotic material/minerals, painted, fluorescent, radioactive, iron oxide coated, inserted with magnets, naturally magnetic, inserted with radio transmitters, or inserted with PIT tags (Hassan and Ergenzinger, 2005; Hassan and Roy, 2016). Tracers provide a means to measure the travel distance of individual grains over a variety of hydrologic conditions over time. They can easily be deployed across accessible portions of the channel, which is of particular interest in complex channels expected to have spatially non-uniform bedload transport. Also, recovery of tracers can be conducted at low-flow, so there is no need for trying to make, for example, direct bedload measurements, at flood flows. The total displacement of tracer particles from deployment to recovery is known as the ‘path length’ (Einstein, 1937) and may describe the aggregate movement caused by a series of discharge events between erosional and depositional sites. When combined with an estimate of the volume of sediment eroded over a defined time interval, the path length can be used to obtain the bedload transport rate (Ashmore and Church, 1998; Church, 2006; Vericat et al., 2017).

In addition to estimating the bedload transport rate, tracers have been used to explore various facets of fluvial sediment dynamics, including stream competence (Milan 2013b), downstream fining (Ferguson and Wathen, 1998), sediment mobility (Mao and Surian, 2010), the timing and duration of sediment entrainment (Olinde and Johnson, 2015) the effects of grain size on particle transport (Church and Hassan, 1992), and the effects of flow strength on particle transport (Schneider et al., 2014). However, the focus of this thesis is more on showing the link between particle dynamics and channel morphology, for which tracers have been used much less. In bar-dominated channels such as the San Juan River, particle path lengths may be equivalent, over the long-term, to the scale and spacing of bars in the channel (Neill, 1987; Pyrce and Ashmore, 2005). If the link between channel morphology and particle dynamics can be demonstrably established, then calculations of bedload transport in these rivers could include inferences
about particle path lengths without the need to measure them directly. However, this must first be verified, which requires particle tracking and monitoring the resultant changes in channel morphology.

While the primary focus of this thesis is on particle transport in a wandering-channel, particle tracking was also conducted on two major tributaries to the San Juan River: Lens and Harris Creeks. These channels have less prominent bar-riffle-pool sequences than the mainstem and are generally steeper and more confined. As such, the path length of tracers in these channels is less likely to be influenced by channel morphology and would be expected to exhibit the more ‘classical’ style of particle displacement found in smaller streams, whereby hydraulic forcing and particle size are the primary controls. Particle tracking in these channels also provides some insight into their relative significance on the mainstem sediment supply.

The following sections will review the controls on bed particle dynamics that have been developed through particle tracking experiments, with a focus on the influence of channel morphology on particle displacements. Additionally, the applicability of PIT tags as a method of particle tracking is reviewed, particularly their utility in wandering channels.

2.2.1 Functional Relationships – Controls on Bed Particle Dynamics

Commonly, field-based tracer experiments have aimed to develop functional relationships between individual particle transport and two primary factors: flow strength and grain size (Hassan and Bradley, 2017). Metrics for flow strength include peak stream power, time-integrated excess peak stream power, and more recently, Phillips and Jerolmack (2014) used an impulse framework (i.e. the momentum of the flow acting on the particle). Grain size relations have been developed using both the absolute particle size and the size of the particle scaled by the median size of the local bed material (Wilcock, 1997).

Hassan and Church (1992) collected datasets from a variety of tracer studies and derived a relationship between the mean tracer path length and excess stream power for single discharge events. While they found that the two variables were positively correlated there was significant scatter amongst the data for gravel-bed rivers. This was attributed to differences in ‘structural constraints’ between the different streams, since channels with well-developed bars showed particle trapping and burial, producing shorter travel distances than ‘unconstrained’ particles that were transported along the bed surface.

In a 17 year experiment using magnetic tracers in a small gravel-bed channel – Carnation Creek, British Columbia – Haschenburger (2013) compared several metrics of tracer dispersion with the time-integrated excess stream power. By differencing the discharge of the transporting event(s) and the critical discharge
for gravel entrainment, this metric captures the total amount of energy available to mobilize tracers, integrated over the duration of flood events. She found that the mean path length of tracers was positively related (power-law) to the excess stream power for a particular mobilizing event. The variability in grain dispersal also increased with excess stream power, as the ‘front-running’ tracers were more rapidly dispersed than the central tracers. Haschenburger (2013) noted that these relations effectively described the magnitude of tracer dispersion but failed to capture the details of individual particle displacements. Over time, tracers were preferentially deposited and stored in bars relative to the rest of the channel, and further, specific reaches of the channel accumulated more tracers than others (potentially due to local characteristics, such as channel planform). A similar observation was made by Ferguson et al. (2002) on the dispersion of magnetic tracers in a small gravel-bed channel in Scotland – Allt Dubhaig. Expanding upon the results from an initial two-year study of tracer dispersion (see Ferguson and Wathen, 1998), they noted that the virtual velocity of tracers, that is the travel distance divided by the duration of competent flow, showed a significant slowdown when monitored over an eight year period. The reduction in tracer transport, when monitored over the longer-term, was ascribed in part to burial and storage of tracers in riffles and bars. These studies provide evidence that the hydraulic control on particle transport may hold true for small streams and/or for shorter time-scales, but that the complexities of particle movement, especially over longer time-scales, is influenced by the morphodynamics of the channel (e.g. bar storage and migration).

Summarizing data from multiple field-based tracer studies, Church and Hassan (1992) and Hassan and Church (1992) found that mean tracer path lengths were better correlated with the size of the particle relative to the median size of local subsurface bed material, rather than simply the absolute size of the grain. For tracers larger than the local $D_{50}$ there was a rapid decline in path length with increasing size, whereas for tracers smaller than the local $D_{50}$ average path lengths were less dependent upon grain size. Church and Hassan (1992) suggested that travel distances for particles smaller than the median were more influenced by trapping in the interstices of larger particles rather than their absolute size. Wilcock (1997) explained the non-linear grain size-travel distance relationship as a product of the partial sediment mobility regime, in which the finer fraction of the bed is fully mobilized (i.e. all sizes are mobilized) but transport of the coarse fraction is controlled by grain size (i.e. not all sizes move, or they are moved shorter distances). Data from more recent tracer studies exhibit a large amount of scatter when plotted against the Church and Hassan (1992) scaled grain size-travel distance relation, though they follow the same general trend (see Hassan and Bradley 2017 and Vázquez-Tarrío et al., 2018). In addition to the inertial, hydraulic and hiding effects acting at the grain scale, Pyrce and Ashmore (2005) posited that size sorting
around bars may affect the path length of different grain sizes (e.g. coarse particles are trapped on the bar head and fine particles are deposited on the bar tail). Though bar scale sorting of particle sizes has yet to be tested using field-based tracer data.

2.2.2 Channel Morphology Relation with Bed Particle Dynamics

The view that hydraulic forcing drives individual particle transport in gravel-bed rivers permeates the literature (Hassan and Bradley, 2017). Yet many tracer studies have noted that differences between tracer path length distributions and theoretical models are largely caused by tracers accumulating at distinct regions related to the channel morphology (e.g. Bradley and Tucker, 2012; Liébault et al., 2012). One of the key observations that has been reported in tracer studies is the tendency for tracers to be preferentially transported to and stored in gravel bars in channels with riffle-pool-bar morphologies, particularly over longer time-scales (e.g. Ferguson et al., 2002; Haschenburger, 2013). This should perhaps not be a surprising observation, since bars are by definition an expression of the displacement, transport and deposition of individual particles. In channels where bars are the dominant macroscale bedform, it follows logically that particle path lengths exist related to the spacing and/or development of the bars. However, the morphologic control on particle path lengths has been relatively under-emphasized and under-studied in the literature and warrants further investigation, particularly for bar-dominated channels.

Pyrce and Ashmore (2003b) provided an extensive review and analysis of the role of channel morphology on particle path lengths using previously published field-based tracer data. They found that positively skewed path length distributions occurred for low-discharge events. In contrast, both higher-magnitude floods and in channels with well-developed bar morphologies, the data followed either bi- or multi-modal distributions, with path length modes representative of depositional features in the channels, typically bars. However, they noted that available field data were insufficient to definitively examine the influence of channel morphology on tracer path lengths.

In simple physical experiments, Pyrce and Ashmore (2003a) explored the role of bars in individual particle transport in a modelled riffle-pool channel. They found that 55-75% of tracers were deposited on the initial bar downstream of their starting position, and that at high-discharges (i.e. those at which bar morphology actively developed), the tracer path length distribution tended to exhibit a primary mode of deposition at the bar apex. At lower discharges, at or around the critical discharge for gravel entrainment, positively skewed path length distributions were observed, with deposition focused at the initial riffle and bar head downstream. Using this same dataset, Pyrce and Ashmore (2005) related the spatial pattern of
tracer deposition to bar growth and development. They observed that during the early stages of bar formation from a straight, plane-bed channel, tracers were transported across the bar surface and towards the bar apex. As the bar developed, tracers began to be primarily routed around the bar, along the margin with the thalweg, resulting in deposition at or downstream of the bar apex, indicative of downstream bar migration. This sequence of bar development is very similar to the observed pattern of bar growth in the Fraser River by Church and Rice (2009). In a more recent flume experiment, Kasprak et al. (2015) demonstrated that tracer path lengths were closely related to erosional and depositional processes associated with bar development. In a modeled braided channel, they found that the average tracer path length was commensurate with confluence-diffuence spacing. Similar results have been yielded from more recent modeling of braided channels (Middleton et al., 2019)

In a synthesis and re-analysis of previously published tracer data, Vázquez-Tarrío et al. (2018) attempted to identify the influence of both hydraulic controls and channel morphology for a range of channel types. They found only a weak positive correlation between stream power and mean tracer travel distance across the dataset. However, they also scaled tracer travel distances by a ‘morphological length scale’ of each respective channel type. For example, travel distances in riffle-pool channels were divided by 5.2 times the channel width (i.e. the average riffle-riffle spacing) and travel distances in step-pool channels were normalized using an equation that defines step-pool spacing. The scaled mean tracer travel distances had a stronger correlation with stream power, indicating that channel morphology was responsible for some of the scatter in the data and that tracer transport has some dependence on channel morphology. In comparing particle movement between different channel types, Vázquez-Tarrío et al. (2018) noted that large particle displacements were typical of plane-bed and step-pool channels, while transport rarely exceeded one morphological length scale unit for riffle-pool channels (i.e. tracers tended to remain within one riffle-pool-bar sequence). This suggests that average particle path lengths should be related to morphologic changes within riffle-pool sequences in these channels, which can then be used for morphological bedload estimates.

2.2.3 Particle Tracking using Passive Integrated Transponders

In recent years tracer studies in fluvial environments have increasingly used PIT tags to track bedload sediment since they make it easy to track individual particles efficiently and tend to have a higher recovery rate than other methods, such as painted or magnetic tracers (Chapuis et al., 2015). PIT tags are small, cylindrical glass capsules that operate using radio frequency identification (RFID) technology. There are two main parts to PIT tag systems – the PIT tag and an antenna. PIT tags are installed in individual stones,
deployed in the channel, and are searched for using the antenna. Technical details regarding PIT tag systems are explained in Chapter 4.

There are several factors which make PIT tags an effective and desirable technology for tracking bedload transport. They are relatively inexpensive compared to active transponders ($5 USD per PIT tag vs. $100 USD per active transponder – Arnaud et al., 2015), they have a long battery life (up to 75 years – Hassan and Roy, 2016), they are robust and resistant to abrasion and breakage (Cassel et al., 2017), and they have unique codes allowing individual particles to be distinguished from one another. Furthermore, as smaller PIT tags are being developed an increasingly wide range of sediment sizes can be tracked (Hassan and Roy, 2016).

The first study to track fluvial bedload transport using PIT tags was conducted by Nichols (2004) in the Walnut Gulch Experimental Watershed in Arizona. The technique was subsequently employed for a variety of studies on small and shallow-water streams achieving recovery rates consistently above 80 % (e.g. Lamarre et al., 2005; Carré et al., 2007; Lamarre and Roy, 2008). The applicability of PIT tags in larger rivers (channel width > 80 m) was first explored by Rollet et al., 2008 on the Ain River, France. They recovered just 36 % of tracers after one year. More recently, Chapuis et al. (2015) achieved a recovery rate of 40 % on the Durance River, France (width = 290 m), while Arnaud et al. (2017) recovered between 11 and 43 % of their tracers over multiple surveys across four years on the Old Rhine, Switzerland (width = 97 m). Recovering a high fraction of tracers is important to the statistics of particle tracking, since low recovery rates may not reflect particle displacements of the entire population. Both deep burial of tracers and large transport distances outside of the surveyed reach have been cited as primary reasons for low recovery rates (Rollet et al., 2008; Chapuis et al., 2015). Chapuis et al. (2015) and Arnaud et al. (2015) both noted that improvement in antenna detection ranges is an important consideration for future PIT tag tracking surveys in larger rivers. These studies provide a template for experimental and equipment design in large rivers, though the low recovery rates indicate that there is room for improvement. There are still many questions about the practical utility of using PIT tags in these environments, such as: what are the maximum depths that tracers are buried in these rivers, how far do the ‘frontrunning’ tracers move, how does the deployment strategy affect the path length distribution, and what is the most efficient method of searching for tracers over large areas of channel? With these questions in mind, particle tracking in the San Juan River provided the opportunity to learn more about optimising deployment and recovery strategies for future PIT-tagged tracer stone studies in large rivers. Increasing tracer recovery rates in large rivers is crucial to obtaining a more complete, and more accurate, understanding of bed particle
movement in these systems, and allows for more definitive interpretations to be made regarding the relative controls on particle dynamics.

2.3 Geomorphic Change Detection

Since the movement of individual particles and the resultant channel morphology are interlinked, especially in large dynamic rivers, it is necessary to monitor net changes in channel morphology to provide context to tracer transport and deposition. With recent advances in surveying technologies, such as differential GPS systems, airborne LiDAR (Light Detection and Ranging) sensors, terrestrial laser scanners (TLS) and Unmanned Aerial Vehicles (UAVs), geomorphologists are increasingly able to produce high-resolution digital elevation models (DEM) of the Earth’s surfaces over large spatial scales (Notebaert et al., 2009; Smith et al., 2016). For fluvial geomorphologists, this has provided a means to monitor reach-scale changes in channel morphology over long reaches and at high-resolution (Vericat et al., 2017). By conducting sequential surveys, DEMs can be differenced to model net changes in the channel temporally (Notebaert et al., 2009; Wheaton et al., 2010a). Major applications of the geomorphic change detection method are to estimate the change in sediment storage volume within a reach for bedload transport equations (Fuller et al., 2003b; Wheaton et al., 2010b), to provide insights into the active layer dimensions (Peirce et al., 2018; Middleton et al., 2019), and to quantify the rates and relative importance of specific fluvial processes (Wheaton et al., 2013; Kasprak et al., 2015, Vericat et al., 2017). When coupled with particle tracking, DEMs of difference (DoDs) also provide insight into the direct link between individual particle dynamics with the overall morphodynamics of the river, and can provide reach-scale sediment budgets and transport rates.

The first (and to the author’s knowledge, only) attempt at coupling particle tracking and repeat high-resolution topographic surveys for a large, wandering gravel-bed river was carried out by Chapuis et al. (2015) on the Durance River, France. In this study, changes in channel morphology were captured via repeat topographic surveys using a real-time kinematic GPS unit. Mobilized tracers remained within a single riffle-pool sequence, and tracer burial was tied to downstream bar migration. They noted that areas of erosion on the DoD corresponded well to mobilized tracers, and that areas of deposition were likely indicative of areas where unrecovered tracers were buried. This study provides some basic insights into individual particle transport in wandering rivers and the relationship with channel morphology. However, there are still aspects of the particle transport-channel evolution relationship in wandering channels that have not been addressed. The lateral development and downstream migration of bars and bends, that is typical of wandering channels, suggests that particle transport must be focused on the lateral and
downstream margins of bars, yet the direct link between these processes has merited little attention in the bedload tracing literature. The relationship between bed particle dynamics and channel evolution in a wandering channel is one of the primary focuses of this thesis and was investigated by coupling particle tracking and geomorphic change detection analysis.

2.3.1 Active Layer Depth
In addition to illustrating the spatial patterns of erosion and deposition in a river, the vertical elevation changes in DoDs provide insight into the variation of the active layer depth and lateral extent. The term ‘active layer’ is broadly used by fluvial geomorphologists to refer to the upper layer of the streambed in which bedload transport occurs (Church and Haschenburger, 2017). For smaller streams with plane-beds, this is conceptually thought of as sheet of uniform thickness typically less than two particles deep (Hassan and Bradley, 2017). However, in larger rivers with more complex morphologies and higher rates of bedload transport, the concept of a ‘morphological active layer’ was proposed by Ashmore et al. (2018). This refers to the “bed sediment layer mobilized as part of the transport process in short time periods related to channel-forming processes such as channel avulsion, bend and confluence scour, bar migration and channel pattern reconfiguration” (p. 1). As such, the morphological active layer varies both laterally and vertically across the active channel area, with depths on the scale of the maximum vertical change in bedforms. Estimates of the active layer depth provide context to tracer burial, giving a maximum depth at which tracers may be buried. But little is known to date for wandering type rivers, so this thesis will provide needed data in regard to active layer dimensions in wandering channels, which can ultimately be used to estimate the morphologic bedload transport rate (Ashmore and Church, 1998; Haschenburger and Church, 1998; Church, 2006).

2.4 Rationale for Research
Channel morphology is a net result of individual particle displacement. Therefore, particle path lengths must exist related to the development of the dominant macroscale channel morphology (Ashmore and Church, 1998). The reciprocal nature of bedload transport and channel morphology has long been recognized (Church, 2006), yet tracer studies have tended to place limited emphasis on the interplay of channel morphology and bed particle dynamics. Most field-based tracer studies have been limited to small riffle-pool (e.g. Milan, 2013a; MacVicar et al., 2015), step-pool (e.g. Lamarre and Roy, 2008; Dell’Agnese et al., 2015) and plane-bed channels (e.g. Gaeuman, 2013; Imhoff and Wilcox, 2016), with less attention focused on intermediate to large-scale channels. In these smaller systems, particle transport appears to be driven by hydraulic controls, and much attention has been paid to developing relationships between
average particle travel distances with characteristics of stream flow and particle size (Hassan and Bradley, 2017). Empirical and theoretical models have been used to describe path length distributions in channels with low rates of sediment transport, though there is often scatter between modeled distributions and the field data, produced by tracers accumulating in distinct areas related to the channel morphology (e.g. Bradley and Tucker, 2012). Questions arise about whether the principles controlling bed particle dynamics in small, simple streams are transferable to channels with more complex morphologies, where features such as bars and riffles constrain particle pathways. Evidence from simple physical experiments suggests that for bar-dominated rivers, the channel morphology exerts the primary control on path lengths during high-magnitude floods (Pyrce and Ashmore, 2003a). To date, there has been limited investigation of this topic in the field, where conditions are both more complex and varied.

Wandering gravel-bed channels are fundamentally defined by an unstable channel, in which changes in channel planform and morphology may occur over relatively short time periods. In these channels, it is plausible to expect that individual particle transport is dictated by the evolution of the channel morphology, in particular the development of bars. Studies of large wandering channels have tended to focus on qualitative descriptions of river sedimentology and morphology (e.g. Desloges and Church, 1987; Church and Rice, 2009) or on quantifying planform and morphologic changes via repeat topographic surveys (e.g. Fuller et al., 2003ab; Burge, 2006). Our understanding of individual particle dynamics in these systems comes from only a small number of field-based tracer studies (Liébault, et al., 2012; Chapuis et al., 2015) and from extrapolating results in scaled-down physical models of alternate bar channels (Pyrce and Ashmore 2003a; 2005). Therefore, further research is required to extend our understanding of bedload transport in wandering channels. Specifically, the link between bed particle dynamics and bar development in these channels has been understudied. By coupling particle tracking and geomorphic change detection analysis, the research in this thesis aims to fill this gap in our knowledge and deepen our understanding of the fundamental role that bars play in bedload sediment transport in gravel-bed rivers.

Capitalizing on technological advances in both particle tracking techniques and topographic surveying, the research for this thesis focuses on making the direct link between individual particle movement and developments in channel morphology for a wandering gravel-bed channel – the San Juan River, British Columbia. Particle tracking was accomplished using PIT tagged tracer stones. Previous studies have yielded promising results using PIT tags to track bedload sediment, and recommendations have been outlined to optimise recovery rates in large rivers (see Chapuis et al., 2014; Arnaud et al., 2015). This study provides the opportunity to assess the practical implications for using PIT tags in a large wandering
channel, which may help inform future bedload tracking studies in similar rivers. Repeat airborne LiDAR surveys before and after the tracer monitoring period were made available for this thesis by the BC Ministry of FLNRRD, and in conjunction with the PIT tag tracer dataset, enable exploration into the link between particle path length and burial depths with overall channel morphodynamics. Particle tracking in the two major tributaries to the lower San Juan River, Lens and Harris Creeks, also allow exploration into the bed sediment dynamics and relative importance of these channels on the mainstem sediment supply.

Overall, the research in this thesis is guided by the following primary questions:

1. In a dynamic, bar-dominated channel, do bed particle path lengths exhibit a morphologic ‘signal’ associated with bar dynamics, in addition to the effects of hydraulic forcing?
2. Is the long-term pattern of channel wandering, caused by lateral bar accretion and bank erosion, reflected by short-term patterns of particle transport and deposition?
3. What specific deployment and surveying strategies are required to successfully conduct PIT tag tracer experiments in large, complex rivers?
Chapter 3: Study Area

3.1 San Juan River

The San Juan River, also known by its native name, the Pacheedaht, is located on the southern portion of Vancouver Island, British Columbia, draining an area of about 730 km$^2$. The name Pacheedaht is shared by the river and the local First Nation band (PFNTI, 2019). The river outlets to Port San Juan on the Strait of Juan de Fuca near to the town of Port Renfrew (Figure 3.1).

![Figure 3.1. Location of the San Juan River Watershed.](image)

3.1.1 Physiography

The San Juan River valley follows a major east-west fault with distinct topography and bedrock geology on the north and south sides. North of the San Juan River the terrain is rugged, with mountain peaks exceeding 1200 m (Alley, 1974). Bedrock on the north side of the valley is diverse, consisting of a series of intrusive and volcanic units, primarily of the Westcoast Crystalline Complex, Island Plutonic Suite, Vancouver Group and Bonanza Group (BCGS, 2018). South of the river the valley rises steeply to a broad plateau with a maximum elevation of 800 m (NHC Ltd., 1994). The hillslope is dissected with gullies, each typically draining less than 10 km$^2$ (Millard, 2013). This side of the valley is underlain almost exclusively by metamorphic rocks of the Leech River Complex (BCGS, 2018).
During the Pleistocene, the San Juan Valley was overridden by ice (probably of the Cordilleran Ice Sheet) and thick till deposits are present along the lower valley (Alley, 1974). Glacial striations and streamlined landforms such as roche moutonées indicate ice movement was south-southwest, and the sporadic glaciolacustrine and glaciofluvial deposits along the valley are a result of glacial lakes present during deglaciation (Alley, 1974). On the north side of the lower San Juan River, glacial terraces and elongated ridges run near-parallel to the mainstem channel, constraining the width of the floodplain on this side of the river. These features appear to constrain the position of the northern tributaries to the main channel.

### 3.1.2 Climate and Hydrology

The San Juan River Watershed is part of the Coastal Western Hemlock Zone, which has on average the wettest climate of the 14 biogeoclimatic zones in British Columbia (Pojar et al., 1991). The valley faces west and is exposed to storms from the Pacific Ocean. There are no climate stations within the watershed, though the Port Renfrew climate station is located close to the mouth of the San Juan River (48°35′30″ N, 124°19′35″ W). Monthly trends in precipitation and temperature are presented in Figure 3.2. Normal (1981-2010) annual temperature at Port Renfrew is 9.3 °C (ECCC, 2019). The average daily temperature is warmest in August (15.6 °C) and coldest in December (3.8 °C). Normal (1981-2010) annual precipitation is 3505 mm of which 99% is rainfall and 1% is snowfall (ECCC, 2019). The wettest month is November (575 mm) and the driest month is July (51 mm). Though nearly all precipitation is rainfall at the valley bottom, there is some snowfall in the interior of the watershed at higher elevations (NHC Ltd., 1994).

![Figure 3.2. Mean monthly precipitation and temperature at the Port Renfrew Climate Station](image)
The Water Survey of Canada (WSC) installed a hydrometric gauging station (08HA010) in the lower San Juan River in 1959 (48°34'38" N, 124°19'02" W). However, in 1984 the station was relocated 1.5 km upstream because the original location was under tidal influence at high tide. In 1997 the station was moved again, this time relocated 0.5 km downstream to its current position (Figure 3.15).

Over the period of record, the annual hydrograph has a maximum instantaneous discharge of 1180 m$^3$/s (Dec. 26$^{th}$, 1980) and a mean discharge of 48.9 m$^3$/s. Since 1960 the mean annual discharge appears to be consistent, with no systematic increase or decrease over time (Figure 3.3). The maximum instantaneous discharge also appears consistent, although there was a period between 1990-2015 where no flood exceeded 1000 m$^3$/s (WSC, 2019). Overall, peak floods have exceeded 1000 m$^3$/s at least nine times, of which four occurred between 1961-1968.

![Figure 3.3. Mean annual discharge at hydrometric station 08HA010 between 1960-2018. Gaps in the record do not reflect mean discharges of 0 m$^3$/s, but are a result of data not being captured that year either because of damage to, or relocation of, the gauging station (Data from: WSC, 2019)](image)

The hydrograph of mean monthly discharge shows that flow is highest from November to January, and then steadily declines to a minimum of 4.5 m$^3$/s in August (Figure 3.4). This follows the trend in monthly precipitation (Figure 3.2), or more specifically the trend in monthly rainfall. There does not appear to be a peak in the hydrograph in the Spring that would reflect snowmelt effects. Breaking down the mean monthly average discharge by decade shows that there are some changes in the hydrograph over time (Figure 3.5). One noticeable change is a decrease in mean discharge in October and an increase in November from the 1960-1969 period compared with the rest of the data. NHC Ltd. (1994) attributed this
to the later arrival of Pacific storms since 1969. Mean discharges for the January-March period display the most variation by decade though there does not appear to be a consistent trend over time. This variation is likely reflective of the timing of precipitation events.

**Figure 3.4.** Mean monthly discharge at hydrometric station 08HA010 between 1959-2017 (Data from: WSC, 2019)

**Figure 3.5.** Mean monthly discharge by decade at hydrometric station 08HA010 between 1959-2017 (Data from: WSC, 2019)
A hydrograph of peak discharge values for the period of this study (2015-2018) is presented in Figure 3.6. From 2015-2018, minimum peak discharges occurred from July to September, and maximum peak discharges occurred between October and May. Twice during this period peak discharge exceeded 1000 m$^3$/s: on November 19$^{th}$, 2017 (1002 m$^3$/s) and January 28$^{th}$, 2016 (1022 m$^3$/s). These floods were particularly flashy, reaching peak discharges and returning to base flow in 24-36 hours. Hydrographs of the largest peak flood for each of the three seasons of tracer deployment are presented in Figure 3.7. In the winter of 2016-17, the peak discharge of 743 m$^3$/s was about 27 % less than peak floods from the other two years. However, the falling limb of the hydrograph was much slower to return to base level, and overall the flood was sustained for a longer period.

There are some sources of uncertainty in values for the San Juan River rating curve. For one, there is currently a mid-channel bar developing at the site of the gauging station. This has altered the hydraulic geometry of the cross-section and will in turn affect the stage-discharge relationship. There are two large sources of uncertainty for discharge values at the upper end of the rating curve:

1. The rating curve was developed using stage-discharge measurements manually collected by the WSC at moderate or low discharges only, as it is impossible to safely take measurement during peak floods.
2. During peak floods the banks are almost certainly overtopped at the gauging station. The river’s natural levees allow overtopping water to be dispersed across the floodplains and will result in an inaccurate upper end to the rating curve as the stage-discharge relationship will differ outside of the bankfull channel.
Figure 3.6. San Juan River hydrograph from September 2015 to September 2018. (Data from: WSC, 2019)
Figure 3.7. Hydrographs for the peak floods during each winter of the tracer experiment: (a) January 28th, 2016 (b) January 18th, 2017 (c) November 19th, 2017
3.1.3 Forest Harvesting and Restoration Work in the Watershed

During the latter half of the twentieth century, the San Juan River Watershed was intensely logged, with over 25% of the watershed area harvested (NHC Ltd., 1994). From 1952 to 1992, NHC Ltd. (1994) identified 128 landslides in forested terrain and 428 landslides in logged terrain. When assessed per unit area, this reflected a nine times greater disturbed area and sediment yield in logged terrain compared to forested terrain. NHC Ltd. (1994) concluded that the total supply of sediment to tributaries had tripled relative to what would have occurred absent forestry impacts over this period. Increased sediment supply resulted in changes to the morphology of the lower San Juan River including: an increase in the size of bars, a straightened mainstem channel with no secondary channels present, and an increase in the width to depth ratio of the mainstem (NHC Ltd., 1994). Coincident with changes in channel morphology, fish stock in the river declined (Burt and Palfrey, 2011). Because of these findings, the San Juan Stewardship Roundtable (a committee of stakeholders in the watershed including provincial and federal government ministries, local First Nations, and industry) directed restoration efforts in the watershed to promote recovery of river conditions more favourable for fish habitat. Restoration work included deactivation of high-risk logging roads, landslide revegetation, and restoration of gullies (SJASC, 1997, 1998, 1999; EBA Engineering Consultants Ltd., 2001). Additionally, gravel bars in the lower mainstem were planted with willows in 1998 to trap sediment and provide habitat for the growth of successional species (Muller and Muller, 1998; Switzer, 1998). Further willow planting was conducted from 2015-2017 (Figure 3.8).

![Figure 3.8. Planted willows on Bar 6 after < 1-year](image)
3.1.4 Channel Morphology

The San Juan River main channel is over 50 km long with a total relief of 690 m. Mainstem headwaters flow from north to south, confined to a canyon. At the confluence with Floodwood Creek, the river turns west and flows through the San Juan Valley. Here, the alluvial reach of the San Juan River begins downstream of the Bear Creek Main Bridge, as the river exits a canyon and large expansive floodplains sprawl across the valley bottom. This section of the San Juan River would best be characterized as a ‘wandering channel’ in that it displays characteristics of both meandering and braided rivers (Church, 1983). Riffle-pool-bar sequences are the primary macroscale bedforms in the alluvial channel, with bars typically on the order of several 100 metres long and up to 100 m wide (Table 3.1). The width of the active channel (defined here as the portion of the channel likely altered by annual floods) varies between 50-150 m, and the reach-average slope is about 0.0011. Though the San Juan River currently flows through a single mainstem channel at low-flow (with one exception at the Harris Creek confluence), planforms maps from NHC Ltd. (1994) show that the current channel pattern is simpler than historic channel patterns as secondary channels have been infilled and abandoned since 1955. The alluvial reach ends in an estuary at the Port San Juan inlet. Tides influence the river’s flow as far upstream as Fairy Lake (Figure 3.12).
Channel banks are generally dominated by a silt and sand matrix with few pebble clasts (Figure 3.9). The alluvial banks are easily eroded and provide a source of fine material to the channel. At a few locations, metasedimentary bedrock outcrops are exposed, providing higher flow resistance locally. Riparian vegetation along the alluvial reach includes red alders (*alnus rubra*) and black cottonwoods (*populus trichocarpa*), with conifers such as western hemlock (*tsuga heterophylla*), western red cedar (*thuja plicata*) and Sitka spruce (*picea sitchensis*) more prevalent farther from the water’s edge.

Bars are composed primarily of gravel and sand and there is a general trend of downstream fining of surface sediment calibre both within and between bars. Based on field observations, gravel bars are armoured, particularly at bar heads. However, no bulk size sampling analysis was conducted, and the precise subsurface grain size distribution is unknown. To make referencing them easier, bars in the lower San Juan River were numbered. Bar 1 is the farthest upstream and subsequent bars are named in ascending order. Characteristics of mainstem bars seeded with tracers as well as nearby bars are presented in Table 3.1. In this study, particle tracking focused on Bars 6, 7, and 15 in the mainstem (Figure 3.15). These locations were chosen based on accessibility, and because they were each planted with willows as part of the restoration work, so monitoring changes in bar morphology and dynamics was of particular interest and importance to the San Juan River Roundtable.

**Table 3.1.** Characteristics of gravel bars in the San Juan River from 2015. Bars in bold are locations where tracers were seeded.

<table>
<thead>
<tr>
<th>Gravel Bar</th>
<th>Area (m²)</th>
<th>Length (m)</th>
<th>Average Width (m)</th>
<th>Exposed Bar Area (m²)</th>
<th>Vegetated Area (m²)</th>
<th>Planted Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar 6</td>
<td>57,550</td>
<td>561</td>
<td>103</td>
<td>23,556</td>
<td>33,994</td>
<td>7,822</td>
</tr>
<tr>
<td>Bar X</td>
<td>3,660</td>
<td>248</td>
<td>15</td>
<td>3,660</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bar 7</td>
<td>37,717</td>
<td>550</td>
<td>69</td>
<td>19,994</td>
<td>17,724</td>
<td>3,533</td>
</tr>
<tr>
<td>Bar 8</td>
<td>11,570</td>
<td>292</td>
<td>40</td>
<td>11,570</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Bar 15</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bar 15</td>
<td>27,814</td>
<td>621</td>
<td>45</td>
<td>27,814</td>
<td>0</td>
<td>10,369</td>
</tr>
<tr>
<td>Bar 16</td>
<td>7,096</td>
<td>268</td>
<td>26</td>
<td>7,096</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Using georectified aerial photographs from 1995, 1999, 2002, 2005 and 2011 as well as orthophotographs and LiDAR DEMs from 2015 and 2018, the BC Ministry of FLNRRD digitized channel boundaries for the San Juan River over time. The channel boundaries were mapped in a GIS and vetted by research geomorphologist, Tom Millard. In the 1995-2011 channel mapping, the exact position of the channel boundary was ambiguous for some locations, in particular where riparian vegetation overhangs the river.
However, channel boundaries were more precisely delineated for 2015 and 2018 because DEMs helped reveal the break between the active channel and floodplain for these areas. Historic channel boundaries have been plotted over the 2018 imagery for each reach of the San Juan River seeded with tracers in Figure 3.10.

Consistent with the definition of a wandering channel, the San Juan River has been laterally unstable between 1995 and 2018, with overall channel widening. Since 1995, the meander around Bar 6 has gradually migrated downstream (Figure 3.10a). On the inside of Bar 6, the channel boundary appears to have shifted substantially between 1995 and 2005, though is more stable in recent years. The fact that the left bank has continued to retreat between 2005 and 2018, despite the right bank remaining relatively stable, suggests that in-channel deposition related to the lateral development of Bar 6 is responsible for forcing the channel to shift towards and erode the left bank. Similar processes appear to be occurring along the Bar 7 section of channel, with channel widening related to bank erosion opposite Bar 7 (Figure 3.10b). Changes in the channel boundaries around Bar 15 were less extensive than changes observed around Bars 6 and 7 (Figure 3.10c). The right bank along the inside of Bar 15 has remained fairly stable, while the left bank has retreated since 1995, though only minimally since 2011.
In 2015, a topographic survey of the San Juan River was conducted using an airborne LiDAR sensor (TRS Inc., 2018a). The LiDAR point cloud was processed to produce a bare-earth digital elevation model (DEM) and further converted to a relative elevation model (REM) by subtracting the minimum elevation along the mainstem channel from the DEM (i.e. by removing the channel slope from the DEM and making topography between the upper and lower parts of the valley relative to each another). A detailed description of how the REM was generated can be found in Appendix E of Olson et al. (2014). REMs are extremely useful tools to visualize past and present fluvial features along river floodplains since elevation increases away from the main channel, highlighting floodplain morphology, rather than increasing.

**Figure 3.10.** Changes in the San Juan River channel boundaries from 1995 – 2018 for (a) Bar 6, (b) Bar 7, and (c) Bar 15. Black arrows depict the primary direction of changes over time.
upstream along the channel. An REM of the alluvial reach of the San Juan River is presented as three images in Figures 3.12-3.14. The REM highlights some interesting morphological features in the river. Upstream of Fairy Lake, two oxbow lakes are located on the right bank floodplain, indicating a more sinuous planform in this area historically (Figure 3.13). Between the two oxbow lakes and Fairy Lake, there is a series of prograding fronts that have a similar appearance to the modern-day banks, perhaps evidence of the path that the river took historically (Figure 3.13). The REM also reveals natural levees on either side of the mainstem as the floodplain slopes gently away from the river. There are channels running along the edge of the floodplain, constrained by elongate ridges parallel to the mainstem. It appears from the REM that overbank flood flows would drain from the mainstem to these channels, though it is not entirely clear that this is the case. These natural levees are also present along Harris and Lens Creeks (Figures 3.13 and 3.14). Most of the mainstem bars have an inner chute channel along the bank (Figure 3.11), suggesting that at high flows the bars are disconnected from the banks entirely.

**Figure 3.11.** Tail of Bar 5 with inner chute channel at low-flow. The blue arrow depicts flow direction.
Figure 3.1. REM of the San Juan River from Fairy Lake to the Port San Juan inlet. Flow is right to left.
Figure 3.13. REM of the San Juan River from the Harris Creek confluence to Fairy Lake. Flow is right to left.
**Figure 3.14.** REM of the San Juan River from the Bear Creek Main bridge to Lens Creek. Flow is right to left.
3.2 Harris and Lens Creeks

The two largest tributaries (by drainage area), Harris and Lens Creeks, both join the lower alluvial reach of the San Juan River from the north bank, 5-8 km upstream of Fairy Lake (Figure 3.15). Harris Creek drains 145 km², and Lens Creek drains 123 km². A set of tracers were deployed in the alluvial reach of each tributary about 2 km upstream of their respective confluences with the mainstem. Both channels have a similar morphology, with short sequences of riffle-pool-bar triplets located at irregular intervals between long stretches of channel without discernible macro-scale bedforms. These rivers are best described as “plane-bed” channels using Montgomery and Buffington’s (1993) channel classification system. Between the site of tracer deployment and the confluence with the mainstem, Harris Creek has an active width of 50 m and an average slope of 0.0022. Lens Creek is narrower, with an active width of 40 m and an average slope of 0.0027.

**Figure 3.15.** Location of the five tracer deployment study sites: Bars 6, 7, and 15 on the San Juan River, Harris Creek and Lens Creek.
Chapter 4: Methods

Two primary datasets were collected and used in this study. Bed particle tracking was conducted for the San Juan River, Harris and Lens Creeks using PIT tags. Morphologic changes in the channels over the tracer monitoring period were captured via repeat aerial LiDAR surveys. In this chapter, the methods used in tracer stone deployment and tracking are outlined followed by a description of the steps involved in geomorphic change detection analysis.

4.1 Tracer Stone Deployment and Tracking

From 2015-2017, 909 tracer stones were deployed at Bar 6, 7, and 15 in the San Juan River, 242 tracers were deployed in Harris Creek, and 218 tracers were deployed in Lens Creek (Table 4.1). The following sections will describe the approach used in the construction, deployment, recovery and analysis of tracer stones.

<table>
<thead>
<tr>
<th>Location</th>
<th>Deployment Date</th>
<th># of Tracers Seeded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar 6</td>
<td>November 30th, 2015</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>October 12th, 2016</td>
<td>134</td>
</tr>
<tr>
<td></td>
<td>September 17th, 2017</td>
<td>142</td>
</tr>
<tr>
<td>Bar 7</td>
<td>September 22nd, 2016</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>September 27th, 2017</td>
<td>131</td>
</tr>
<tr>
<td>Bar 15</td>
<td>October 12th, 2016</td>
<td>134</td>
</tr>
<tr>
<td></td>
<td>September 28th, 2017</td>
<td>136</td>
</tr>
<tr>
<td>Harris Creek</td>
<td>October 12th, 2016</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>November 1st, 2017</td>
<td>138</td>
</tr>
<tr>
<td>Lens Creek</td>
<td>October 12th, 2016</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>September 28th, 2017</td>
<td>115</td>
</tr>
</tbody>
</table>

4.1.1 Tracer Stone Preparation

The purpose behind using tracer stones was to infer the path length of bedload in the San Juan River and tributaries. For meaningful conclusions to be drawn from the results of this study, the deployed tracer stones need to be a representative sample of the distribution of bed material in the channels. Therefore,
Wolman counts (Wolman, 1954) were conducted to determine the grain size distribution of surface sediment at each site. Sampling was conducted by targeting coarse areas on dry, exposed sections of gravel bars. A measuring tape was stretched over the surface, and the b-axis of a minimum of 100 individual grains was measured and recorded, as suggested by Eaton et al. (2008) (actual counts ranged from 102-123 particles). Grain sizes were binned by b-axis diameter using the standard Wentworth scale (Table 4.2) and plotted as cumulative distributions by percentage of grains finer than each bin (Figure 4.1). After determining the grain size distribution, candidate tracer stones were selected from the four bins centered around the median grain size, this included grain sizes of 22-32 mm, 32-45 mm, 45-64 mm, and 64-91 mm. Additionally, in 2017 a set of 12 tracers between 91-128 mm were deployed to determine mobility of the coarsest particles. The fine end of the distribution was not well-represented (particularly for Bar 15) (Figure 4.1) because RFID tags generally did not fit in particles smaller than 22 mm, and it was presumed that the clasts into which tags did fit would be more susceptible to breaking after deployment in the river. Additionally, the density of fine particles would be more significantly altered as a larger percentage of the particle volume would be removed to install the RFID tag.

Table 4.2. Wentworth scale of grain size. Size classes in bold represent the range of tracer stone sizes.

<table>
<thead>
<tr>
<th>Grain Size Class (mm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 180</td>
<td>Coarse cobbles</td>
</tr>
<tr>
<td>128 - 180</td>
<td></td>
</tr>
<tr>
<td><strong>91 - 128</strong></td>
<td>Fine cobbles</td>
</tr>
<tr>
<td>64 - 91</td>
<td></td>
</tr>
<tr>
<td>45 - 64</td>
<td>Very coarse gravel</td>
</tr>
<tr>
<td>32 - 45</td>
<td></td>
</tr>
<tr>
<td><strong>22 - 32</strong></td>
<td>Coarse gravel</td>
</tr>
<tr>
<td>16 – 22</td>
<td></td>
</tr>
<tr>
<td>11 - 16</td>
<td>Medium gravel</td>
</tr>
<tr>
<td>8 - 11</td>
<td></td>
</tr>
<tr>
<td>5.6 - 8</td>
<td>Fine gravel</td>
</tr>
<tr>
<td>&lt; 5.6</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.1. Grain size distribution plots for the five tracer sites.
Gravel and cobbles in the San Juan River have two distinct shapes: flat, discoidal particles and round, spherical particles. The two shapes are generally reflective of the sediment source, as discoidal particles are typically metasediments from the south side of the valley, while spheres are more commonly igneous rocks entering the San Juan River from the north side of the valley (McQueen et al., 2016). Tracer selection was heavily biased towards spheres, as the flatter discoidal particles are fragile and more prone to shattering during drilling. The metasedimentary discs are less dense (~ 2.75 g/mL) than igneous particles (~ 2.97 g/mL) and may be expected to be transported farther. However, this may be offset by the proclivity of these particles to become imbricated on the bed surface once deposited, resulting in a more stable bed fabric (Church et al., 1987). In 1995, Hattingh and Illenberger conducted a tracer experiment using synthetic particles to determine the effect of grain shape on mobility and transport. The results from their study indicated that spheres travelled farther than discs, and that this shape-effect was greatest at lower flows, as particles were carried in suspension at higher flows. They suggested that spheres (and elongated rod-shaped particles) were more easily entrained than discs (and bladed particles) because they protrude out from the bed and roll more easily. However, in this experiment, synthetic particles were made to a constant density of 2.4 g/cm³, which is not reflective of the disparity in particle density in the San Juan River. Overall, the effect of particle shape on transport is not well established on the San Juan River, and the logistics of particle drilling dictated that spheres were more suitable candidates for tracer stones. Furthermore, the selection of tracers from the 22 - 32 mm size class was biased towards elongate, rod-shaped particles so that tags could be inserted along the long axis (or, a-axis) of the particle. This may mean that transport data for the tracers is not reflective of the discoidal particles in the channel. However, since tracer path lengths are expected to be morphologically dominated in the San Juan River, physical properties of the particles, such as shape and density, may be secondary at most.

After collecting tracer stones from the field, they were brought back to the lab for drilling. A cavity approximately 35-40 mm deep was drilled in each particle using a bench drill press and a diamond core drill bit. A custom drill press tray was designed and built by a metal fabricator, to allow a range of different shapes and sizes of stones to be clamped in place. To prolong the life of drill bits, a hose supplying cold tap water was directed over the bit during drilling. A second hose was attached to a spout exiting the tray allowing water and sediment to be drained. A fine-meshed sieve was placed in a sink to catch waste sediment. Drill bits wore out and were replaced after 50-100 stones.

RFID tags used in this project were half duplex passive integrated transponders (PIT tags) purchased from Oregon RFID (Oregon RFID, 2019). PIT tag systems consist of two components: a transponder (i.e. the PIT
tag) and a reader (i.e. the antenna). In half-duplex systems, the reader produces short magnetic impulses that activate the PIT tag. Once the PIT tag becomes active it communicates with the reader by transmitting the unique RFID code associated with that tag via radio waves. The reader’s cycle of producing magnetic impulses and waiting for a response from the PIT tag repeats in user-defined time intervals. Half-duplex systems have larger detection ranges than full duplex systems, which will read and respond concurrently (Schneider et al., 2010). The PIT tags used for this study are classified as low-frequency because they operate at 134.2 kHz. Low-frequency tags are ideal for tracking in coastal and fluvial environments because their signal can pass through water and can penetrate most non-metallic objects (e.g. sediment, wood, etc.) better than high and ultra-high frequency tags (Chapuis et al., 2014; Schneider et al., 2010).

In 2015, the initial set of tracer stones were created using a variety of 12-, 23-, and 32-mm long PIT tags based on the size of the stone. The size of the PIT tag is proportional to the maximum linear distance at which the antenna can detect the tag (i.e. the read range). Chapuis et al. (2014) tested the limits of detection for different sized tags and found that on average the read range of the 12-mm tag was only 37% as far as the 32-mm tag, and that the 23-mm tag read range was only 75% as far as the 32-mm tag. Using their wand antenna, this corresponds to average read ranges of 13, 27, and 35 cm for the 12-, 23-, and 32-mm tags respectively. Due to a low recovery rate of tracers from 2015-2016 (see Section 5.1), tracers created in 2016 were only inserted with 23- and 32-mm PIT tags, and in 2017 tracers were installed with 32-mm tags only. The decision to eliminate the usage of smaller tags was made to improve recovery rates, especially of the smaller sized tracers.

PIT tags were secured within the tracer stones by infilling cavities with a high strength masonry epoxy. After allowing the epoxy to cure, all tracers were painted bright colours using non-toxic epoxy and/or spray paints. This provided a visual aid to make locating them in the field more efficient. An identification number was written on each tracer stone, distinct from the unique ID of the PIT tag. Though this step was not strictly necessary, it helped facilitate note taking during the deployment and recovery of tracers. It also acted as backup identification in the case that the PIT tag was damaged or destroyed after being deployed in the river. An inventory of all tracer stones was completed prior to deployment by scanning and recording both the RFID and written ID numbers.

4.1.2 Tracer Stone Deployment
Tracer stones were deployed in the fall prior to winter flooding (Table 4.1). Clusters of tracers were spaced at intervals of one to two metres across the channel, along a ‘launch line’ perpendicular to the direction of flow (Figure 4.2). Each cluster generally had one tracer of each size class for a total of 100-142 tracers
across the launch line. Launch lines along the mainstem were selected to span the head of one bar, a riffle, and the tail of the opposite bar (Figure 3.15). The one exception to this was in 2016, the Bar 6 launch line was moved downstream of the riffle so that a portion of the launch line intersected a pool, and the effect of initial seeding position could be assessed. Tracer stones in Harris and Lens Creeks were deployed with the same spacing and similar number of tracers as those in the mainstem (Table 4.1). Launch lines were chosen 100-200 m downstream of their respective bridges in the hope they would not be directly visible to the public. The Harris Creek launch line extended across the middle of a bar and adjacent pool, the Lens Creek launch line spanned a riffle or plane-bed channel. To keep the launch lines in the same position year to year, rebar was hammered into the substrate and a GPS point was recorded to mark the transect endpoints.

During deployment, particles on the surface of the riverbed were removed and replaced with tracer stones. This was intended to reflect natural particle positions and mimic local bed texture, since previous research has shown that travel distances for unconstrained particles are higher than for locked or buried particles (Hassan and Church, 1992; Hassan and Bradley, 2017; Vázquez-Tarrió et al., 2018). When looking at the hydrographs for the three years of tracer deployment (Figure 3.6), moderate floods preceded the highest discharge event each year, and it can be assumed that tracers were integrated into the riverbed prior to the event(s) expected to do most of the work in transporting particles. Therefore, it is not expected that bias induced by unconstrained starting positions is critical for this study.

Figure 4.2. Tracer launch lines for Bar 6 (left) and Bar 7 (right).
4.1.3 Tracer Stone Recovery

Tracer stone recovery was conducted during the low-flow season at the end of July through August for 2016 to 2018. This allowed the greatest portion of the channel to be searched because pool area is at a minimum at low-flow. However, some pools more than a meter deep were still present and not wadable, and these areas were omitted from the searching process. Two antennas were used for searching for tracers, both purchased from Biomark®. The ‘BP Plus Portable’ antenna is a two-metre long ‘wand’ antenna that is used in concert with the HPR Plus reader (Figure 4.4a). This antenna can read 32-mm PIT tags at a maximum distance of 45-50 cm away. However, read range is not consistent because the “detection zone”, that is the three-dimensional area in which the transponder and reader can transfer information, is anisotropic (Arnaud et al., 2015; Chapuis et al., 2014). Read range increases when the antenna approaches the tag orthogonal to the long axis of the tag and reaches a minimum when the antenna approaches the tag parallel to the long axis (Figure 4.3). Testing in the lab prior to fieldwork appeared to confirm detection zone anisotropy with the BP Plus Portable antenna. The wand antenna was the sole antenna used for tracer recovery in 2016, resulting in a low recovery rate (see Section 5.1), and was used only as a supplementary tool to a larger antenna for subsequent years. It was particularly useful for searching small areas as it is light and efficient to use. It was also ideal for searching areas where tracer clustering was suspected. In densely populated areas PIT tag signals interfere with one another and antennas are often unable to detect some, or potentially all, of the tags in the vicinity (Lamarre et al., 2005; Chapuis et al., 2014). The effect of signal shadowing is greatest when antennas have large read ranges and is reduced using smaller antennas with lower read ranges. Therefore, the BP Plus Portable wand was an ideal antenna for searching the launch lines, where immobile tracers cluster, since it has a relatively small read range and can quickly scan areas from multiple directions.

Figure 4.3. PIT tag (left) and the theoretical detection zone (right) from Chapuis et al., 2014.
The second antenna used was a 50’ (15 m) Cord Antenna System. This system consists of a portable enclosure, a J-box, and the cord antenna. The portable enclosure houses an IS1001 reader (Biomark, 2019), and the J-box provides the junction between the portable enclosure and the cord antenna. The purpose behind using this antenna was that it can cover a much larger surface area than the wand antenna, making it ideal for searching large areas efficiently. The cord antenna also has a larger range of detection than the wand antenna, with a maximum read range around 1.75 m. For use in the field, the cord antenna was secured to a 15’ x 5’ (5 m x 1.5 m) rectangular PVC pipe frame. The frame held the cord in a (semi-) rigid structure stabilizing the antenna and allowing it to keep a high current. The antenna and pipe were mounted to a backpack frame using a series of ropes, pulleys and cams. The user would stand in the centre of the rectangle wearing the backpack and could manipulate the height of each corner of the antenna to help navigate obstacles and changing topography in the field (Figure 4.4b). The backpack frame was also loaded with two Li-ion batteries, the IS1001 reader, and the J-box required to operate the antenna. When using the Antenna Cord System, a tablet was connected via Bluetooth to the reader, and the BioStat app was used to monitor ID numbers of detected tags in case multiple tracers were found in one area. The BioStat app’s auto-tune function (ATF) was used to optimize the current settings and detection range prior to searching.

Figure 4.4. (a) Biomark’s BP Plus Portable antenna. (b) Biomark’s Antenna Cord System.
The protocol for searching the channel was to conduct a sweep of the launch line first using the wand antenna. Several more cross-sectional passes were conducted with the wand antenna to about five metres downstream. Any tracers found were dug up and removed, and the area was then searched a second time using the cord antenna to find remaining tracers buried deeper than the wand antenna’s range of detection. The cord antenna would then be used to carefully continue the search in a downstream direction, scanning the dry and wet portions of the channel separately. Generally, the most efficient search method involved walking roughly 50 m paths parallel to the channel, marking the edge of each swath with bright tent stakes or sticks wrapped in flagging tape. On subsequent paths up- or downstream, the antenna edge could be lined up with the line of sticks/stakes demarcating the previous extent searched. About a half-metre of overlap was used between search paths to ensure the area was searched thoroughly and completely. Once the cord antenna detected a PIT tag it continuously beeped and flashed a light until the tag was no longer within its range of detection. A rough location of the tracer stone was then estimated by walking forwards and backwards to determine the limit of detection along one axis, and then approaching the area orthogonally and determining the limit of detection along a second axis. A bright yellow peg was then staked into the surface to mark the rough location of the tracer and the RFID number was recorded. After sweeping a section of the channel, the cord antenna was set down, turned off, and the wand antenna was used to refine (if possible) the location of any detected tracers.

For recovered tracers, a GPS waypoint and waypoint accuracy were recorded using a handheld Garmin GPS. To increase the accuracy of GPS waypoints, they were recorded using the ‘Waypoint Averaging’ function, whereby the device takes multiple readings at the same location and averages the value to refine the position (Garmin, 2019). The Garmin calculates a waypoint error by taking the standard deviation of all readings during waypoint averaging. Waypoint errors were typically zero or one metre, though some waypoints were recorded with an error as large as 2-3 metres. GPS error was largest on overcast days and for less exposed locations, for example, tracers deposited on the channel edge close to tree stands. Though this error is admittedly a rough estimate, measurements are accurate enough for this study as average travel distances were typically more than 100 m. For tracers deposited within the first 20 metres or so downstream from their initial position, their location was determined by stretching a wind-up measuring tape across the launch line, and then measuring to the tracers’ final position by using a second measuring tape perpendicular to the launch line and recording both the downstream distance and distance along the launch line. This method was assumed to be more precise for measuring short distances than recording a GPS waypoint. When tracers were located, the burial depth, grain size, RFID number,
written number, and any other pertinent notes were recorded in addition to the GPS data. Burial depth was measured, somewhat crudely, by placing the handle of a shovel along the excavated hole to represent the bed surface, and a handheld measuring tape used to measure to the top of the tracer stone to the nearest half-centimetre (Figure 4.5). However, some tracers were buried too deep or found in deep water and could not be physically recovered. For these particles, a GPS point was taken to mark the estimated position of the unrecovered tracer. It was assumed that the inaccuracy of marking a rough tracer location was likely an error within the GPS instrument error.

![Tracer stone burial. Measurements were recorded to the nearest 0.5 cm, from the top of the particle to the bed surface.](image)

The maximum downstream extent surveyed differed for each location, though generally the first two bars downstream of the seeding site were searched. By this point most tracers had been recovered, and the distance between finding successive tracers became increasingly large. Overall, the process of searching for tracers was labour-intensive and took approximately three weeks of three to four people working ten-hour days.

4.1.4 Tracer Data Analysis
Waypoints marking the final positions of tracers were uploaded to a GIS and stored in a geodatabase as a point feature class. Tracers that travelled short distances, and whose locations were measured from the
launch line, were digitized and added to this feature class. Field notes were entered into Excel spreadsheets, and also imported as attribute data to the point feature class containing tracer recovery locations. Tracer stone data was organized into separate files by study site, deployment year and recovery year. For example, separate feature classes were produced for tracers deployed on Bar 6 in 2015 and recovered in 2016, as for those deployed in 2015 but recovered in 2017 or 2018. This allowed efficient analysis of different subsets of the tracer dataset.

In the literature, two methods of measuring path lengths are most common. The first method is to simply calculate the straight-line distance between the initial and final positions of the tracer stones (e.g. Camenen et al., 2010; Chapuis et al., 2015; Lamarre and Roy, 2008). The second method is to delineate a longitudinal profile along the channel centreline and to project tracer positions onto this profile (e.g. Arnaud et al., 2017; Liébault et al., 2012; MacVicar et al., 2015). The first method is likely most accurate for tracers travelling short distances, particularly in straight sections of channel. However, as travel distances increase, or in sinuous sections of channel, the channel centreline method represents a more realistic measure of the distance travelled, as straight-line distances may include travel over inactive portions of the channel or floodplain (Figure 4.6). The difference between the two methods is negligible for shorter path lengths but becomes increasingly important for longer path lengths. An example of this is presented in Figure 4.7 for tracers deployed on Bar 6 from 2017-2018. In this example, the difference in path length between methods is less than 25 m for tracers recovered in the first 200 m or so downstream but increases quickly beyond this as the thalweg starts to meander around a bend. Path lengths were measured using the channel centreline method for this study because it likely reflects a truer estimate of the distance travelled and actual pathway for the farthest moving tracers.

Path length distributions were analysed for tracers that moved beyond ten metres downstream from their initial position. Any tracers recovered within the first ten metres of the launch line were considered immobile and removed from path length analysis to account for the uncertainty in measurements of the tracers’ initial and final positions.
Figure 4.6. Example of different measures of path length in a sinuous section of channel at Bars 6-7.

Figure 4.7. Comparison of methods used to measure path length – L. Path lengths here are from tracer stones deployed at Bar 6 from 2017-2018.
4.2 Geomorphic Change Detection

4.2.1 Data Description

To determine channel changes over the tracer monitoring period, repeat surveys were used to measure topographic change. For this study, two aerial LiDAR (and imagery) surveys were made available by the province of British Columbia, Ministry of FLNRRD. The initial survey was conducted on October 23rd-24th, 2015 and the latter survey was conducted on February 10th-11th, 2018, both by Terra Remote Sensing Inc. (TRS Inc., 2018ab). The overall surveyed area included the alluvial reach of the San Juan River, the lower portions of Lens and Harris Creeks, as well as Hemmingsen Creek and the Gordon River (Figure 1 in TRS Inc., 2018ab). Geomorphic change detection (GCD) analysis was conducted for all five locations seeded with tracers, though Bars 6 and 7 were treated as a single reach, resulting in a total of four sites: Bars 6-7, Bar 15, Lens Creek, and Harris Creek.

For the 2015 LiDAR survey, 37 % of the area had > 12 points/m² on the first return point cloud, with an average point density of 12.8 ± 7.2 points /m². The 2018 LiDAR survey had a greater overall point density, as 75 % of the area had > 18 points/m², with an average point density of 28 ± 16 points /m². Along the river corridor, point density ranged from zero in deep water, to over 10 points /m² on flat exposed surfaces, with intermediate point densities (typically around 2-6 points /m²) in vegetated areas. TRS Inc. reported a vertical accuracy of 0.026 m for the 2015 survey (2018a) and 0.032 m for the 2018 survey (2018b). This accuracy was based on a comparison of known static and post-processing-kinematic (PPK) GPS survey locations with a triangular irregular network (TIN) surface derived from the bare earth LiDAR data. A series of real-time-kinematic (RTK) GPS point were also collected on identifiable features such as road intersections or paint markings for a second accuracy check, though these data were not published. A complete description of LiDAR acquisition, processing, and the internal and external accuracy checks are found in the respective survey reports (TRS Inc., 2018ab) and summarized in Appendix A.

The LiDAR sensor used during aerial surveys (Reigl LMS-Q780) operates by emitting near infrared lasers. As such it is unable to penetrate deep water (i.e. pools), as near-infrared wavelengths are absorbed by water. During the 2015 survey, the San Juan River was at a stage of 2.2 m discharging 10 m³/s, whereas during the 2018 survey the river was at a stage of 2.6 m, discharging 39 m³/s. This meant that some areas of the channel, typically bar heads and margins, that were inundated during the 2018 survey were exposed for the 2015 survey. As a result, the sparse (or non-existent) point density in these locations lead to a high interpolation error locally when generating DEMs from the 2018 LiDAR point cloud. This limited the
analysis because real geomorphic change could not be distinguished from error due to differences in stage for these areas.

Another implication of the lack of topographic data in the wetted-portion of the channel, is that complete reach-scale sediment budgets could not be established. While most of the channel could be analysed given the LiDAR coverage, net vertical changes in pools and along the thalweg were not quantified. However, GCD analysis was used to interpret the spatial pattern of erosion and deposition for most of the channel, and to provide an estimate of the order of magnitude of net areal and volumetric change. It should be noted that since there were multiple floods between surveys, scour caused by one event may be compensated locally by fill from subsequent floods (and vice versa), resulting in a negative bias in cumulative deposition and erosion volume estimates (Lindsay and Ashmore, 2001). This does not affect net changes between surveys.

4.2.2 GCD Workflow

GCD analysis was conducted in ESRI’s ArcMap, using the ‘GCD 7 Addin for ArcGIS’ software. This software was developed to perform topographic change detection on raster-based data (Wheaton et al., 2010a), and “has become a well-accepted and standardized method for DEM differencing and volumetric budgeting” (Vericat et al., 2017, p. 135). Perhaps the greatest appeal of this software is that it allows the user to quantify spatially-variable estimates of DEM uncertainties, to propagate these uncertainties through the DEM of difference (DoD), and to assess the statistical significance of these uncertainties in distinguishing real geomorphic change from noise (Wheaton et al., 2010a). Further, the software allows the user to classify the DoD using a mask, segregating the geomorphic change by the mechanism or process that caused the erosion or deposition. A flow diagram depicting the steps performed in GCD analysis is presented in Figure 4.8.
To prepare the data for GCD analysis, the LiDAR point clouds were clipped to the extent of the four study sites, reducing the size of the dataset. Using the built-in function in the GCD toolbar, point clouds were clipped to the extent of the four study sites, reducing the size of the dataset. Using the built-in function in the GCD toolbar, point clouds were...
converted to TINs, and linearly interpolated to generate concurrent rasters (concurrency meaning that rasters share the same extent, the same cell size, and that the cells are perfectly aligned). A sensitivity analysis was performed to determine the ideal balance between a high enough resolution to accurately characterize the surface, but not so high that the file size became too large and processing times became excessive. A resolution of 10 cm was adopted, as higher resolutions resulted in only a small increase in detail but a large increase in file size.

For each location (and for each survey), two surfaces were generated for uncertainty analysis using the built-in tools in the GCD software: a point density raster and a slope raster. The rationale behind using these surfaces is that steep areas with low point density will have high elevation uncertainty, whereas flat areas with high survey point density will have lower elevation uncertainty (Wheaton et al., 2010a). Slope and point density rasters were used as inputs into a fuzzy inference system (FIS), which used a set of user-defined rules to output a spatially variable elevation uncertainty raster. The FIS treats inputs as continuous variables, with the range of possible values categorized using descriptive terms (such as high, moderate, low, none). Each category, or “membership function”, is associated with a specific range of values, though the boundary between membership functions overlaps. The FIS analyses the inputs on a cell-by-cell basis using Boolean logic to enforce the user-defined rules. Like the inputs, the range of possible output values (in this case elevation uncertainty) is divided into membership functions. The rule system used in this study is presented in Table 4.3, and an example of the membership function values is presented in Table 4.4. The rule system was adapted from the default aerial LiDAR FIS, sourced in the GCD software. Membership function values were defined based on known instrument error, the range of slopes and point densities at each study site (for each survey), and the expected vertical changes to occur across the channel. On bars, vertical change may be expected to be small, but span a large surface area, as gravel sheets migrate downstream. These areas would be categorized in the FIS as low slope and (usually) high point density and would therefore be expected to have a low elevation uncertainty, meaning that only a small vertical change is required for them to be distinguished from noise. Conversely, banks are categorized by the FIS as areas of high slope and (usually) low point density, and therefore require a large vertical change to be assessed as real geomorphic change. Since banks in the San Juan River are two to three metres high, bank retreat resulted in large vertical changes, and was still recognized as real change by the GCD analysis.

The FIS-derived elevation uncertainty rasters for each survey were then combined using the formula:

\[ \delta u_{DOD} = \sqrt{(\delta Z_{2018})^2 + (\delta Z_{2015})^2} \]
Where, \( \delta u_{DoD} \) is the propagated error in the DoD, and \( \delta Z \) is the elevation uncertainties for the DEMs (Wheaton et al., 2010a). The significance of the uncertainty was then determined using probabilistic thresholding at both the 80 and 95 % confidence intervals. In this method, a t-score is calculated using the following formula:

\[
t = \frac{|z_{2018} - z_{2015}|}{\delta u_{DoD}}
\]

Where the numerator is the absolute value of the DoD (Wheaton et al., 2010a). The t-score is then converted to a probability. For the 80 % threshold, any changes with a probability less than 80 % are removed, and for the 95 % threshold, any changes with a probability less than 95 % are removed from the DoD. These methods are useful for determining the confidence that changes are real, and distinct from noise. The propagated elevation uncertainty raster (\( \delta u_{DoD} \)) is then converted to volumetric errors, and ± one standard deviation of the volumetric error is reported as the uncertainty associated with volumetric changes in the thresholded DoD (Wheaton et al., 2013). Note that volumes are calculated on a cell-by-cell basis as the product of the elevation change and cell dimensions (i.e. 0.1 x 0.1 m).

**Table 4.3.** Two input fuzzy inference system for elevation uncertainty, based on slope and point density.

<table>
<thead>
<tr>
<th>Slope (°)</th>
<th>Point Density (points/m²)</th>
<th>Elevation Uncertainty (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>Average</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Medium</td>
<td>None</td>
<td>Extreme</td>
</tr>
<tr>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Medium</td>
<td>Medium</td>
<td>Average</td>
</tr>
<tr>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>None</td>
<td>Extreme</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
<td>Extreme</td>
</tr>
<tr>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>Average</td>
</tr>
</tbody>
</table>
Finally, values from thresholded DoDs were classified using a mask to breakdown the different types of erosion and deposition. The mask was created by classifying 2015 and 2018 orthophotos as either gravel, vegetation, or water through manual digitization of polygons. The classified images were then combined using the union function in ArcMap. The output polygon feature class was given an attribute field to identify changes in classification between 2015 and 2018. Table 4.5 presents the possible types of change and the physical interpretation of these changes. The image-classification mask was then input into the GCD software and used to segregate the thresholded DoD. A key reason for doing the budget segregation was to parse out the volume of topographic change that occurred in regions that were classified as gravel in 2015 but water in 2018. These values gave an indicator of volumetric change potentially caused by the higher water level in 2018 and not real geomorphic change.

**Table 4.4. Example membership function values (from Bar 15 FIS). The values here are written as discrete numbers, though in the FIS the boundary between membership functions is fuzzy.**

<table>
<thead>
<tr>
<th>Slope [°]</th>
<th>Point Density (points/m²)</th>
<th>Elevation Uncertainty (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low 0 - 5</td>
<td>None 0</td>
<td>Low 0.0 - 0.10</td>
</tr>
<tr>
<td>Medium 5 - 25</td>
<td>Low &gt; 0 - 0.5</td>
<td>Average 0.10 - 0.25</td>
</tr>
<tr>
<td>High &gt; 25</td>
<td>Medium &gt; 0.5 - 5</td>
<td>High 0.25 - 0.75</td>
</tr>
<tr>
<td>High &gt; 25</td>
<td>High &gt; 5</td>
<td>Extreme 0.75 - 1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change in Surface Class</th>
<th>Interpretation of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravel to gravel</td>
<td>erosion or deposition on bars</td>
</tr>
<tr>
<td>gravel to vegetation</td>
<td>imprecise delineation of gravel/vegetated areas</td>
</tr>
<tr>
<td>gravel to water</td>
<td>erosion of bars, or inundation of bars due to higher stage in 2018</td>
</tr>
<tr>
<td>vegetation to gravel</td>
<td>imprecise delineation of gravel/vegetated areas</td>
</tr>
<tr>
<td>vegetation to vegetation</td>
<td>erosion or deposition of vegetated area</td>
</tr>
<tr>
<td>vegetation to water</td>
<td>bank erosion</td>
</tr>
<tr>
<td>water to gravel</td>
<td>in-channel deposition, or lateral/longitudinal growth of bars</td>
</tr>
<tr>
<td>water to vegetation</td>
<td>imprecise delineation of water/vegetated areas</td>
</tr>
<tr>
<td>water to water</td>
<td>N/A (no data for water-water areas)</td>
</tr>
</tbody>
</table>
Chapter 5: Results and Interpretation

The following chapter presents all results from the tracer experiment in addition to geomorphic change detection analysis. Tracer recovery rates are given in Section 5.1. Tracer path length distributions for each site are presented in Section 5.2. Section 5.3 describes the morphological units in which tracers were deposited. Following this, the effects of discharge, grain size, and seeding position on tracer mobility and path lengths are examined in Sections 5.4 – 5.6. Tracer burial data is presented in Section 5.7 and results from geomorphic change detection analysis are presented in Section 5.8. Tracer burial and short-term changes in channel morphology are then compared with long term changes in channel planform in Section 5.9. Finally, the results are summarized in Section 5.10.

5.1 Tracer Recovery Rates

Overall, a recovery rate of 72% was achieved across all locations, varying from as low as 63% (Harris Creek, 2016 deployment) to 81% (Bar 6, 2015 deployment) (Table 5.1). Reported recovery rates in Table 5.1 are calculated using the sum of all recovered tracers found in subsequent surveys, not just the initial survey after deployment. Over 65% of tracers were found in the immediate surveys after deployment, with a small number found in the following two or three years. There were two clear exceptions to this trend. The first exception was the Bar 6 2015 deployment, in this case just 33% of tracers were recovered after one year because only the wand antenna was used for searching and the remaining tracers were likely buried deeper than the antenna’s maximum read range. The implications of this are discussed throughout this chapter, when pertinent to the specific results being presented. The second exception was the Harris Creek 2016 deployment. In this case, nine tracers were found more than a kilometre downstream of the launch line at the confluence with the San Juan River, an area not searched during the first-year survey. In addition, some tracers were recovered in areas previously searched, perhaps an effect of burial during 2016-17 floods and subsequent scour in 2017-18 floods, revealing previously-unrecovered tracers. However, this possible burial and exhumation cannot be confirmed because no topographic surveys were conducted in 2017.

A total of 994 tracers were recovered across all sites during this study, though only 989 were deemed reliable data for statistical analysis ($n_{\text{stat}} = 989$) (Table 5.1). Five tracers were omitted from analysis because their final position appeared to be human-influenced, as they were found carefully placed on fallen trees or by campfires. These five tracers were all from the Harris Creek 2017 deployment (Table 5.1).
5.2 Path Length Distributions

Tracer path lengths for each site were binned into 50 m intervals (25 m for Lens Creek) and plotted as frequency distribution line graphs in Figures 5.1, 5.4, 5.6, 5.8 and 5.10. An interval width of 50 m was selected since macroscale bedforms were typically hundreds of metres long. Thus, binning the data by 50 m intervals made it possible to visualize tracer concentrations within and between these morphologic units. Overall path length distributions are presented together with plots for tracers seeded from each year. Long profiles of the bed surface along the channel centreline are also plotted on the line graphs, with pools depicted by straight lines (reflecting the absence of elevation data from the LiDAR survey in these areas). Key morphologic features were labelled (e.g. bar head, bar apex, riffles, etc.) to allow a comparison of peaks in tracer deposition with channel morphology. While these path length distributions provide a one-dimensional approach to comparing particle movement with channel morphology, they don’t paint the full spatial picture (Pyrce and Ashmore, 2005). Maps showing the final position of recovered tracers are presented in Figures 5.2, 5.5, 5.7, 5.9 and 5.11 to provide further context to path length analysis.

### Table 5.1. Summary of tracer recovery rates by location and year.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year of Deployment</th>
<th>n</th>
<th>( n_r,2016 )</th>
<th>( n_r,2017 )</th>
<th>( n_r,2018 )</th>
<th>( n_f )</th>
<th>( n_{\text{stat}} )</th>
<th>( r (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar 6</td>
<td>2015</td>
<td>100</td>
<td>33</td>
<td>43</td>
<td>5</td>
<td>81</td>
<td>81</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>134</td>
<td>-</td>
<td>88</td>
<td>13</td>
<td>101</td>
<td>101</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>142</td>
<td>-</td>
<td>-</td>
<td>101</td>
<td>101</td>
<td>101</td>
<td>71</td>
</tr>
<tr>
<td>Bar 7</td>
<td>2016</td>
<td>132</td>
<td>-</td>
<td>100</td>
<td>4</td>
<td>104</td>
<td>104</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>131</td>
<td>-</td>
<td>-</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>69</td>
</tr>
<tr>
<td>Lens Creek</td>
<td>2016</td>
<td>103</td>
<td>-</td>
<td>67</td>
<td>8</td>
<td>75</td>
<td>75</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>115</td>
<td>-</td>
<td>-</td>
<td>84</td>
<td>84</td>
<td>84</td>
<td>73</td>
</tr>
<tr>
<td>Harris Creek</td>
<td>2016</td>
<td>104</td>
<td>-</td>
<td>43</td>
<td>22</td>
<td>65</td>
<td>65</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>138</td>
<td>-</td>
<td>-</td>
<td>108</td>
<td>108</td>
<td>103</td>
<td>75</td>
</tr>
<tr>
<td>Bar 15</td>
<td>2016</td>
<td>134</td>
<td>-</td>
<td>94</td>
<td>3</td>
<td>97</td>
<td>97</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>136</td>
<td>-</td>
<td>-</td>
<td>88</td>
<td>88</td>
<td>88</td>
<td>65</td>
</tr>
<tr>
<td>Combined</td>
<td>2015-2017</td>
<td>1369</td>
<td>33</td>
<td>435</td>
<td>526</td>
<td>994</td>
<td>989</td>
<td>72</td>
</tr>
</tbody>
</table>

*NOTE: n - number of deployed tracers; \( n_r \) - number of recovered tracers; \( n_{\text{stat}} \) - number of recovered tracers reliable for statistical analysis; \( r \) - recovery rate (100 \( \times \) \( n_{\text{stat}} \)/\( n \)).*
5.2.1 Bar 6
Bar 6 tracer path length distributions are presented in Figure 5.1. The launch line for Bar 6 was located at the bar head/riffle for 2015 and 2017 but moved 120 m downstream to intersect the pool for the 2016 launch. To allow the path lengths to be plotted on a common downstream axis, the origin was defined as the 2015/2017 launch line and tracer positions are plotted relative to this. This means 120 m was added to the path length of 2016 tracers and the distribution is not strictly a path length distribution, but rather reflects the tracers’ final position relative to the 2015/2017 launch line.

The path length distribution for Bar 6 tracers shows a multi-modal distribution with three distinct peaks in tracer deposition (Figure 5.1). The first peak coincides with a short-transport mode reflective of tracers deposited within the first 50-100 m downstream. Tracers deposited at this distance were found exclusively in 2015 and 2017, and predominantly in the riffle between Bars 5 and 6 as well as the tail of Bar 5 (Figure 5.2). Few tracers were deposited on the bar top at the head of Bar 6.
Figure 5.1. Path length distribution for Bar 6 tracers.
The second peak, and the largest one, occurs at about 200 m, coincident with the bar apex (and adjacent pool). Just over 25% of all mobile tracers were found at this location, with the largest fraction of tracers deposited here from the 2016 launch. From 2015-2018, a sheet of coarse gravel and cobbles approximately one metre thick migrated downstream from the bar head, accreted laterally and forced the main channel towards the outer bank (Figure 5.3). This bedload sheet terminates at the apex of the bar. The downstream extent of this feature in 2015 and in 2018 is labelled on Figure 5.1, highlighting that the growth of this feature coincides with an area of high tracer concentration.

The third peak occurs at about 300 m, just downstream of the bar apex. This peak was present for the 2016 and 2017 tracer distributions, but not for tracers deployed in 2015. This area also reflects a location of bar growth between 2015 and 2018 (see Figure 5.25). A possible explanation for the low concentration of 2015 tracers here may be that the growth of the bar occurred primarily from 2016-2018, after 33% of the 2015 tracers had already been recovered (Table 5.1).
A small fraction of tracers made it past the bar apex and were deposited between 450 and 600 m downstream on the bar tail. This occurred consistently for all three years of tracer deployment. All tracers deposited on the bar tail were smaller than 64 mm and appear to be primarily deposited by a secondary channel dissecting the bar top during higher discharges (Figure 5.2). Only four tracers in total (all smaller than 45 mm) were recovered beyond the downstream extent of Bar 6, three from the 2016 deployment, and one from the 2017 deployment.

![Migrating bedload sheet](image)

**Figure 5.3.** Planform view of the migrating bedload sheet at the apex of Bar 6 (from 2017). Inset shows the ~1 m tall avalanche face at the downstream margin of the sheet.

### 5.2.2 Bar 7

Bar 7 tracer path length distributions are presented in Figure 5.4. Bar 7 tracer path lengths follow a bimodal distribution with a peak at 50 m, reflective of a short-transport mode, and a second peak at 250 m, just downstream of the bar apex. The concentration of tracers deposited in the initial 50 m downstream from the launch line was greater in the 2016 launch (> 15 %) than the 2017 launch (< 5 %) (Figure 5.4). In both cases, mobility of tracers on the left side of the launch line appears restricted, likely due to the growth of Bar X overlapping this section of the launch line (see Sections 5.6 and 5.8). However, for tracers
deployed closer to the channel centre there was a difference in transport between the years. In 2016, tracers appear to be evenly deposited across the riffle/mid-channel bar spanning the first 50 m downstream of the launch line, whereas tracers deployed in 2017 have been exported from this area entirely.

The second mode of tracer concentration was 20-30 m downstream of the bar apex and adjacent pool (Figure 5.4). This peak was consistent for both years of deployment, though slightly higher in 2017. Deposition in this area was spread across the bar top, the pool-bar margin and the pool for tracers deployed in 2017 (note that the deepest sections of the pool were not searched). Tracers from the 2016 deployment were more clustered on the bar top.

A higher concentration of tracers were deposited on the tail of Bar 7 than were deposited on Bar 6, though only a single tracer from the 64-91 mm size class travelled this far (from the 2017 deployment, Figure 5.5). A cluster of tracers were deposited at the riffle between Bars 7 and 8 in 2016, and two tracers travelled beyond this riffle, found in-channel adjacent to Bar 8. While the channel is forced to take a winding course around the apex of Bar 6 as the bar builds out laterally, it follows a straighter planform along Bar 7, perhaps facilitating the transport of tracers past the Bar 7 apex, leading to deposition on the bar tail and downstream riffle. So particle dynamics are reflecting the style and stage of bar development.

![Figure 5.4. Path length distribution for Bar 7 tracers.](image-url)
Figure 5.5. Tracer recovery locations for Bar 7, 2016 (upper) and 2017 (lower) launches.
5.2.3 Bar 15

The path length distribution for Bar 15 tracers shows a multi-modal distribution with four peaks in tracer deposition (Figure 5.6). This pattern was consistent for tracers seeded in both 2016 and 2017. The first peak, at 50 m downstream, reflected a short-transport mode with tracers deposited across the initial riffle, and a few tracers deposited at the head of Bar 15 (in 2016), and the tail of Bar 14 (in 2017) (Figure 5.7). The concentration of tracers in the area was greater for 2016 than 2017, where overall tracer mobility was lower (Figure 5.15).

The second and third peaks occur at 200 m and 400 m downstream, just above and below the bar apex (and adjacent pool). The concentration of tracers at 200 m was higher for the 2017 launch, and generally represented tracers deposited along the pool-bar margin. It is unclear if there was net deposition or erosion in this area, as the bar margin was inundated in 2018, restricting GCD analysis for this area. The concentration of tracers 400 m downstream was again greater for the 2017 launch. Tracers in the area were focused along both the bar top and the pool-bar margin downstream of the bar apex, reflective of vertical and lateral accretion of the bar locally (see Section 5.8).

The fourth peak was at 550 m downstream and represented tracers found in the riffle between the tail of Bar 15 and the head of Bar 16 (Figure 5.7). In 2016, only tracers smaller than 45 mm were transported to this riffle, though in the 2017 launch, two tracers from the 64-91 mm size class were transported to this area. In total, three tracers were found downstream of this riffle, one from the 2016 deployment and two from the 2017 deployment. All three were located on or adjacent to Bar 16.

Figure 5.6. Path length distribution for Bar 15 tracers.
Figure 5.7. Tracer recovery locations for Bar 15, 2016 (upper) and 2017 (lower) launches.
5.2.4 Harris Creek

Harris Creek tracer path length distributions are presented in Figure 5.8. Overall the path length distribution is positively skewed, however there are two peaks in tracer concentration that may be related to morphologic constraints. The first peak occurs at 200 m and was present in the individual distributions for tracers deployed in both 2016 and 2017. This location coincides with both the apex of the bar attached to the left bank, and the first pool downstream of the launch line (Figure 5.9). The tracer recovery location maps (Figure 5.9) show that tracers appear to be preferentially deposited in-channel at this distance as opposed to the bar top, perhaps evidence that the bar is building out into the pool here. A second, much less-pronounced, peak in the path length distribution occurs at 550 m downstream (Figure 5.8). Tracers were deposited at a riffle between alternate bars at this location.

Due to time constraints, only a single path of the channel was searched between 850 m downstream of the launch site and the mouth of Harris Creek. Two tracers were found in this reach, one from each year of deployment (Figure 5.9). At the mouth of Harris Creek there is one final 200 m long bar, which disperses sediment across a riffle and onto a fan-shaped bar in the San Juan River mainstem. A cluster of eight tracers were found in this area during the 2018 survey, all of which were deployed in 2016.

Overall, the effects of channel morphology on tracer path lengths were much less discernable for Harris Creek than on the San Juan River. This may suggest that other controls, such as grain size-sorting or hydrologic forcing, are more important for Harris Creek bedload path lengths than constraints enforced by channel morphology.
Figure 5.8. Path length distribution for Harris Creek tracers.
Figure 5.9. Tracer recovery locations for Harris Creek, 2016 (upper) and 2017 (lower) launches.
5.2.5 Lens Creek

Lens Creek tracer path length distributions are presented in Figure 5.10. Though a recovery rate of 73% was achieved for Lens Creek tracers, a large fraction of them were immobile and recovered at or near the launch line (Figure 5.11 and 5.15). This meant that only a small number of tracers were used in plotting the path length distributions, limiting meaningful interpretation or analysis. Even after removing immobile tracers, the highest peak in the overall path length distribution occurs at 25 m, representing a short-transport mode. Tracer recover location maps show that very few tracers were found on bars in Lens Creek (Figure 5.11). The second highest concentration of tracers, at 275 m, occurs just upstream of a steep riffle between alternate bars, at the end of a long flat stretch of channel. The Lens Creek path length distribution doesn’t appear to tail off completely after the initial 425 m downstream, suggesting that tracers were likely exported downstream of the searched area entirely. This would align with results from tracer studies in other plane-bed channels (see Vázquez-Tarrío et al, 2018, and Figure 6.3), where large path lengths are possible due to the lack of well-developed bars able to constrain particle pathways.

![Path length distribution for Lens Creek tracers.](image)

**Figure 5.10. Path length distribution for Lens Creek tracers.**
Figure 5.11. Tracer recovery locations – Lens Creek, 2016 (upper) and 2017 (lower) launches.
5.3 Tracer Deposition by Morphological Unit
To further investigate the influence of morphology on particle path length, the morphological unit in which tracers were deposited was analysed (Figure 5.12). The channel was classified into three types of unit: low-flow pools, low-flow riffles, and low-flow bars. Additionally, for Harris Creek, one tracer was located in a plane-bed section of channel that was classified as a “run”. During tracer recovery, the morphologic unit in which tracers were recovered was not consistently recorded. However, imagery from 2015, 2016, 2018 and for some locations in 2017 were available, so the morphologic unit in which tracers were deposited could be inferred visually. The extent of each unit can only be defined approximately, and the boundary between units was not sharply defined. For example, the exact transition between a riffle and a pool could not always be precisely delineated, and the lateral separation of bar and pool was somewhat arbitrary, being dependent upon the water level in the imagery. However, between the field notes and available imagery, tracer positions were classified accurately to detect obvious differences in tracer proportions between units. Tracer deposition data presented in Figure 5.12 was also subdivided by

![Figure 5.12. Tracer concentrations across morphologic units.](image)
tracer size class, however, there was no obvious preferential deposition of tracers of any specific size class clustering in any one morphologic unit.

Overall, 77% of recovered tracers on the San Juan River were found in depositional sites – riffles (24%) and bars (53%), and 23% of tracers were recovered in pools (Figure 5.12). In general, tracers that were located in pools tended to be found in the shallower portions of the pool next to the bar. This is likely a reflection of how the channel dynamics are changing overall, as the bars are being built out laterally, and the pools are forced over towards the bank opposite the bar (see Section 5.8). However, it should be re-stated here that the deeper portions of pools were not searched, and so these results may underestimate the fraction of tracers deposited in pools.

For Bars 6 and 7, the highest concentration of tracers was on the bars, at 56 and 67% respectively (Figure 5.12). However, for Bar 15, tracers were more evenly distributed across the units, with 37% recovered in riffles, 35% recovered on bars, and 29% in pools (Figure 5.12). The low mobility of Bar 15 tracers in 2016-17 (Figure 5.15) resulted in a high fraction of tracers remaining in the riffle in which they were seeded. The relatively even spread of tracers deposited in pools and bars can be explained by examining the tracer recovery location map (Figure 5.7), which shows that the pattern of tracer deposition was focused along the bar-pool margin, reflective of the bar accreting laterally.

The high proportion of tracers found in riffles for Lens Creek (68%) is a result of low tracer mobility, as few tracers were transported past the initial riffle in which they were seeded. Harris Creek had the highest fraction of tracers recovered in pools at 50% (Figure 5.12). In Harris Creek, the tracer launch line was spread across a pool, and a bar attached to the left bank (Figure 3.15). This bar and pool extend 450 m downstream of the launch line, so most recovered tracers were found in these two units. The channel above the tracer launch line has a meander, and it appears that flow over the launch line is directed towards the right bank. This observation is supported by the pattern of net erosion on the bar from the Harris Creek DoD (Figure 5.28), perhaps explaining why tracers were preferentially transported to and deposited on the right side of the channel – in the pool.

5.4 Effects of Discharge on Tracer Transport and Entrainment

While the primary objective of this research is to highlight the reciprocal relationship between channel morphology and bedload path lengths, hydraulic controls on tracer path lengths cannot be ignored. Previous research has suggested that flow intensity and discharge play an important role in particle path lengths, particularly for flows only slightly above the critical discharge, when the bed is mostly immobile
Therefore, several metrics capturing flow intensity and/or duration were calculated for each year’s hydrograph, to compare with mainstem tracer path lengths and mobility for each respective year. Harris and Lens Creek tracer path lengths are presented separately, since no direct discharge data was available for these channels, though their hydrographs presumably followed a similar pattern to the mainstem. The three metrics analysed were: peak discharge, total flow volume, and total flow volume above the critical discharge (which from now on will be referred to as the excess flow volume). Typically, peak discharge is considered the primary control on bedload transport (Hassan and Church, 1992; Hassan et al., 1992), but since there were multiple peaks between tracer deployment and recovery, excess flow volume was calculated to capture both the magnitude and duration of flow across multiple large flood events, and to indicate the approximate number of mobilising events that might have occurred.

5.4.1 Critical Discharge Estimation

In this case, the critical discharge provides a metric for the discharge above which gravel entrainment may occur. Obtaining an estimate of the critical discharge will provide a rough idea of the number of significant transport events and their magnitudes. Since no data was available to directly infer the critical discharge, an estimate of the bankfull discharge was calculated using the velocity-area approach, with the assumption that the bankfull discharge roughly approximates the critical discharge. Though gravel entrainment likely occurs at flows lower than the bankfull discharge, the bankfull discharge reflects conditions in which the bankfull dimensions of the river are created, and as such will serve here as a crude approximation of the “channel-forming” or critical discharge. An alternative method of obtaining a critical discharge is through calculations of the critical bed shear stress. However, this approach was not employed since bed shear stress is likely to be highly variable in the San Juan River due to elevation differences associated with riffles, pools, and bars.

A cross-section was generated from the 2015 LiDAR-derived DEM at the Bar 6 tracer launch line. This was a convenient location to estimate a bankfull discharge for a couple of reasons. First, the 2015 LiDAR was able to penetrate the shallow water across the riffle here and a reasonable characterization of the bed surface across the entire cross-section was available. Secondly, two Wolman counts had been conducted at this location previously, so the size of bed material was known. This cross-section profile was used to calculate the hydraulic geometry for the bankfull channel (i.e. hydraulic perimeter, area, and radius). Knowing the hydraulic radius, the reach-averaged slope, and the grain size distribution for this location,
an estimate of the average velocity across the cross-section was calculated from flow resistance equations. Here, the Manning and the Manning-Strickler equations were used to estimate velocity:

\[
\text{Manning equation: } \quad v = \frac{R^{\frac{2}{3}} S^{\frac{1}{2}}}{n} \tag{5.1}
\]

\[
\text{Manning-Strickler equation: } \quad v = a (g R S) \left( \frac{D}{D_{50}} \right)^{\frac{1}{6}} \tag{5.2}
\]

Where \( v \) is the average cross-section velocity, \( R \) is the hydraulic radius (equal to the hydraulic area divided by the hydraulic perimeter), \( S \) is the reach-averaged slope, \( n \) is Manning’s roughness or resistance coefficient, \( g \) is the acceleration due to gravity, \( D \) is a characteristic grain size diameter, and \( a \) is a constant determined by the grain size used (Ferguson, 2013). A sensitivity analysis was conducted by varying Manning’s \( n \) for the Manning equation, based on suggested values for riffle-pool channels from the literature (Montgomery and Buffington, 1997), and by using both the \( D_{50} \) and \( D_{84} \) as the characteristic grain size for the Manning-Strickler equation (Ferguson, 2013). The range of values for average cross-section velocity is presented in Table 5.2.

**Table 5.2. Sensitivity analysis for average cross-section velocity calculations.**

<table>
<thead>
<tr>
<th>Flow-Resistance Equation</th>
<th>Constants Used</th>
<th>( v ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manning</td>
<td>( n = 0.04 )</td>
<td>1.15</td>
</tr>
<tr>
<td>Manning</td>
<td>( n = 0.035 )</td>
<td>1.31</td>
</tr>
<tr>
<td>Manning</td>
<td>( n = 0.03 )</td>
<td>1.53</td>
</tr>
<tr>
<td>Manning-Strickler</td>
<td>( a = 6.74 ), ( D_{50} = 0.045 ) m</td>
<td>1.62</td>
</tr>
<tr>
<td>Manning-Strickler</td>
<td>( a = 7.5 ), ( D_{84} = 0.083 ) m</td>
<td>1.63</td>
</tr>
<tr>
<td>Manning-Strickler</td>
<td>( a = 8.1 ), ( D_{84} = 0.083 ) m</td>
<td>1.76</td>
</tr>
</tbody>
</table>

The bankfull discharge was calculated as the product of the bankfull hydraulic area and average cross-section velocity (at bankfull). Bankfull discharge estimates ranged from 207-317 m\(^3\)/s, with a median value of 285 ± 38 m\(^3\)/s based on the six velocity calculations used. These values were scaled by watershed area, to calculate the equivalent discharge at the hydrometric station, using the following formula:

\[
Q_h = Q_{B6} \left( \frac{A_h}{A_{B6}} \right)^{0.785} \tag{5.3}
\]
Where, $Q_h$ and $Q_{B6}$ are the discharges for the hydrometric station and Bar 6 respectively, $A$ is the watershed area, and the exponent 0.785 was determined by plotting peak flow and watershed area data for the entire province of BC by Coulson and Obedkoff (1998). The median estimate of bankfull discharge at the hydrometric station was calculated as $488 \pm 65 \text{ m}^3/\text{s}$. A second set of calculations were conducted for the Bar 7 tracer launch line, resulting in a bankfull discharge of $530 \pm 70 \text{ m}^3/\text{s}$ at the hydrometric station. Given the inherent uncertainty in both the bankfull discharge calculations, and the assumption that the bankfull discharge approximates the critical discharge, a value of $500 \text{ m}^3/\text{s}$ was chosen as a rough estimate of the critical discharge.

A time-lapse camera was set up along the bank opposite the apex of Bar 6 facing downstream, with images were captured at 15 minute intervals. Time-lapse images of the channel at low-flow and bankfull discharges at Bar 6 are presented in Figure 5.13. The bankfull image is from November 19th, 2017 at 3:45 pm, which was during the rising limb of the largest flood that winter which peaked at 1003 m$^3$/s. The hydrometric station recorded a discharge of 560 m$^3$/s at the time this image was taken, lending credence to the value of 500 m$^3$/s as a reasonable approximation of the bankfull discharge.

A summary of all floods exceeding the critical discharge (500 m$^3$/s) is presented in Table 5.4. Six events occurred in the winter of 2015-16, four events in the winter of 2016/17, and six events during the winter of 2017/18. The relationship between excess flow volume and peak discharge is presented in Figure 5.14. A linear regression combining the three years of data fits with an R$^2$ of 0.82, indicating that the two
variables are strongly related. This reaffirms the knowledge that the largest discharge events during the three years of tracer monitoring were brief, and the peak discharge was not sustained for a long period. Also, since excess flow volume characterizes the amount of flow available to transport bedload sediment, this suggests that the peak discharge should correlate well with tracer path lengths. The relationship between peak discharge and excess flow volume showed some variation year to year (Figure 5.14). Floods during the winter of 2016/17 showed the weakest relationship between the two variables, indicative of less flashy floods, sustained over a longer duration. The winter of 2016/17 also had the fewest number of floods over 500 m$^3$/s, and the lowest peak discharge of the three years. A summary of peak discharge, total and excess flow volumes are presented for each year of tracer deployment in Table 5.3. Though the highest total volume occurred in the 2016-17 season, this season also had the lowest excess flow volume. The highest flow volume occurred in 2017-18, and the highest peak discharge occurred in the 2015-16 season.

![Graph](image)

**Figure 5.14.** Relationship between peak discharge and excess flow volume. The black line represents the least squares regression for all the data and corresponds with the equation and $R^2$ values at the top left of the graph.

**Table 5.3.** Yearly summary of hydrologic variables.

<table>
<thead>
<tr>
<th>Year</th>
<th>$Q_{\text{max}}$ (m$^3$/s)</th>
<th>$\Sigma V$ (dam$^3$)</th>
<th>$\Sigma V_c$ (dam$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015-16</td>
<td>1,022</td>
<td>1,349,047</td>
<td>41,990</td>
</tr>
<tr>
<td>2016-17</td>
<td>749</td>
<td>1,792,792</td>
<td>28,306</td>
</tr>
<tr>
<td>2017-18</td>
<td>1,003</td>
<td>1,541,834</td>
<td>66,963</td>
</tr>
</tbody>
</table>

*NOTE: $Q_{\text{max}}$ is the peak discharge, $\Sigma V$ is the total flow volume, and $\Sigma V_c$ is the excess flow volume.*
5.4.2 Hydraulic Effects on Tracer Mobility

The relative mobility of tracers across the five study sites is presented in Figure 5.15, mobility here meaning the fraction of tracers that moved. Overall, mobility was highest in 2017-18 (82 %), followed by 2015-16 (76 %), and the lowest mobility occurred during the 2016-17 season (65 %). This pattern follows the trend in excess flow volume (Table 5.3), though results from 2015-16 should be acknowledged cautiously due to the low sample number. When comparing mobility for Bar 6 tracers, the only location with three years of data, it appears at first that tracer mobility increased each year chronologically. However, in 2016, the launch line was placed downstream of the Bar 6 riffle, and intersected a pool, a location expected to have a higher rate of erosion. Therefore, results cannot be compared directly. For Bar 7 and Harris Creek tracers, mobility was consistent for the 2016-17 and 2017-18 seasons. Tracer mobility in Lens Creek was lower than both the San Juan River and Harris Creek.

Between the two years with comparable data, 2016-17 and 2017-18, the relative mobility of tracers was generally higher in 2017-18, though this was not consistent across all sites, and interpretation of Lens and

<table>
<thead>
<tr>
<th>Dates of Event</th>
<th>Year</th>
<th>$Q_{\text{max}}$ (m$^3$/s)</th>
<th>$\Sigma V_{cr}$ (dam$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 5-9</td>
<td>2015</td>
<td>811</td>
<td>11349</td>
</tr>
<tr>
<td>December 13</td>
<td>2015</td>
<td>570</td>
<td>1451</td>
</tr>
<tr>
<td>January 21-22</td>
<td>2016</td>
<td>533</td>
<td>366</td>
</tr>
<tr>
<td>January 27-28</td>
<td>2016</td>
<td>1022</td>
<td>19419</td>
</tr>
<tr>
<td>February 15-16</td>
<td>2016</td>
<td>641</td>
<td>2768</td>
</tr>
<tr>
<td>March 10</td>
<td>2016</td>
<td>707</td>
<td>6636</td>
</tr>
<tr>
<td>October 14-15</td>
<td>2016</td>
<td>708</td>
<td>5334</td>
</tr>
<tr>
<td>November 2-3</td>
<td>2016</td>
<td>571</td>
<td>5492</td>
</tr>
<tr>
<td>January 17-18</td>
<td>2017</td>
<td>749</td>
<td>16097</td>
</tr>
<tr>
<td>February 15-16</td>
<td>2017</td>
<td>575</td>
<td>1383</td>
</tr>
<tr>
<td>October 18-19</td>
<td>2017</td>
<td>659</td>
<td>3075</td>
</tr>
<tr>
<td>November 14-15</td>
<td>2017</td>
<td>660</td>
<td>3945</td>
</tr>
<tr>
<td>November 19-23</td>
<td>2017</td>
<td>1003</td>
<td>26161</td>
</tr>
<tr>
<td>January 21</td>
<td>2018</td>
<td>614</td>
<td>2845</td>
</tr>
<tr>
<td>January 30</td>
<td>2018</td>
<td>901</td>
<td>29334</td>
</tr>
<tr>
<td>April 13-14</td>
<td>2018</td>
<td>602</td>
<td>1603</td>
</tr>
</tbody>
</table>

*Table 5.4. Summary of floods exceeding 500 m$^3$/s over the tracer monitoring*
Harris Creek tracer mobility relies on the assumption of flows correlating directly with the San Juan River hydrograph. However, since tracers were exposed to a higher volume of flow above the critical discharge for entrainment in 2017-18 (i.e. $\sum V_{cr}$), it seems reasonable that a larger fraction of tracers deployed in that year were mobilized.

5.4.3 Hydraulic Effects on Tracer Path Lengths
Box plots for mobile tracer path lengths for mainstem and tributary study sites are presented in Figure 5.16. On the mainstem, the lowest median and maximum path lengths occurred for 2015-16 tracers. This is not interpreted to be a result caused by hydrologic conditions, but rather an artefact of using only the wand antenna and searching a shorter distance downstream, resulting in the recovery of just 25 mobile tracers after one year. Therefore, no meaningful interpretation of discharge effects in 2015-16 path lengths were possible. However, similar search methods and conditions for 2016-17 and 2017-18 allow comparability of path lengths between these two years.

In 2017-18, the year with the higher excess flow volume and peak discharge, both mainstem and tributary tracers had larger median and maximum path lengths than in 2016-17 (Figure 5.16). This result seems reliable for mainstem tracers, since recovery rates were similar between the two years (Table 5.1) and it aligns with previous knowledge of the relationship between peak discharge and path length (Hassan and Bradley, 2017). However, the data for tributary tracers should be interpreted more cautiously, as there was bias induced by the low recovery rate of Harris Creek tracers in 2016-17 (41 %) relative to 2017-18 (75 %). An additional nine tracers from the 2016 deployment on Harris Creek were found more than a
kilometre downstream in 2018 and may indicate that the box plot of path lengths presented here is an underestimate for tributary tracers in 2016-2017. Additionally, only 28 % of Lens Creek tracers were mobilized in 2016-17 and included in this plot. Since just 56 mobile tracers were recovered from Lens and Harris Creeks in 2016-17 (Figure 5.16b), the comparison of path lengths between years can only be reported tentatively for these creeks. Overall, median tracer path lengths appear to correlate with peak discharge for this dataset. This makes sense since the amount of flow available to entrain sediment (i.e. \( \sum V_c \)) is directly tied to peak discharge for the San Juan River, and bar building occurs at higher flows. However, as previously described, the details of tracer movement are tied to channel morphology. The combination of flow conditions and changes in channel morphology provide a more complete understanding of particle movement, as flow is required to mobilize the bed, but once mobilized, tracer dispersion is tied to the morphology.

Figure 5.16. Path length distributions for (a) mainstem and (b) tributary tracers recovered after exactly one year. Boxes represent the first and third quartile, with the median depicted by the dark blue line in the centre of the boxes. Whiskers represent the maximum and minimum path lengths of mobile tracers.
5.5 Effects of Grain Size on Tracer Transport and Entrainment

In addition to linking particle movement with channel morphology and flow conditions, previous research has indicated that grain size influences tracer path lengths (Church and Hassan, 1992; Wilcock, 1997). Wilcock (1997) provided a physical explanation of the relationship between grain size and path length, describing a partial mobility regime in which the entrainment and transport of sediment larger than the $D_{50}$ is strongly influenced by grain size, but sediment finer than the $D_{50}$ is fully mobilized. Pyrce and Ashmore (2005) also proposed that size-dependent path lengths could arise as an effect of grain size-sorting effects around bars, whereby like-sized particles may cluster at distinct locations (i.e. coarse particles at bar heads, fine particles on bar tails). Therefore, for this thesis, tracer path lengths were plotted by their respective grain size class to assess any effects of particle size on path length, and morphologic features (e.g. bar head, bar apex, riffle) were identified to help examine if clustering of like-sized particles was related to bar sedimentation (Figure 5.18). The fraction of bed material represented by each tracer size class is presented in Table 5.5 to give further context to the results. Generally, the median size of bed material was around 45 mm, so tracers in the 22-32 and 32-45 mm classes reflect particles smaller than the median, and tracers in the 45-64 and 64-90 mm classes reflect particles larger than the median (Table 5.5). Bar 15 bed material had a finer distribution than the other sites, with a median around 30 mm, so only the 22-32 mm class of tracers contains particles smaller than the median (Table 5.5).

Table 5.5. Fraction of bed material represented by each tracer size class for each study site.

<table>
<thead>
<tr>
<th>Tracer Size Class (mm)</th>
<th>Fraction of Bed Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bar 6</td>
</tr>
<tr>
<td>22 - 32</td>
<td>$D_{20} - D_{30}$</td>
</tr>
<tr>
<td>32 - 45</td>
<td>$D_{36} - D_{55}$</td>
</tr>
<tr>
<td>45 - 64</td>
<td>$D_{55} - D_{75}$</td>
</tr>
<tr>
<td>64 - 90</td>
<td>$D_{75} - D_{90}$</td>
</tr>
</tbody>
</table>

Prior to interpreting the path length-grain size relationship, it is important to note that the recovery of tracers from each size class was not equal. Coarser tracers were consistently recovered at a higher rate than finer particles across the five study sites, with the highest recovery rate of 85 % achieved for 64-91 mm tracers, and the lowest rate of 47 % achieved for 22-32 mm tracers (Table 5.6). It is possible that smaller particles were more prone to breakage than larger ones, since a higher fraction of the stone’s
volume was altered during drilling, potentially reducing the particle’s integrity. However, Cassel et al.’s (2017) annular flume experiments showed that low recovery rates of PIT tagged tracer stones in gravel-bed rivers are not well explained by particle breakage, as PIT tag destruction occurred in just 2.2 % of particles. The most likely causes of low tracer recovery rates are: signal interference due to particle clustering, burial depths in excess of the antennas’ maximum detection range, and/or transport farther downstream than was searched (Cassel et al., 2017; Lamarre et al., 2005). The latter situation would of course mean that the reported path lengths for low recovery rate size classes do not reflect the distribution of path lengths for the entire population of tracers of that size class and are underestimates.

Table 5.6. Recovery rate for each tracer grain size class.

<table>
<thead>
<tr>
<th>Grain Size (mm)</th>
<th>n</th>
<th>n_r</th>
<th>r (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 - 32</td>
<td>334</td>
<td>157</td>
<td>47</td>
</tr>
<tr>
<td>32 - 45</td>
<td>365</td>
<td>271</td>
<td>74</td>
</tr>
<tr>
<td>45 - 64</td>
<td>376</td>
<td>313</td>
<td>83</td>
</tr>
<tr>
<td>64 - 90</td>
<td>282</td>
<td>240</td>
<td>85</td>
</tr>
<tr>
<td>&gt; 90</td>
<td>12</td>
<td>8</td>
<td>67</td>
</tr>
</tbody>
</table>

5.5.1 Grain Size Effects on Tracer Mobility
The relative mobility of tracers of each size class is presented in Table 5.7. Overall, 82 % of the 22-32 mm tracers were mobilized, and conversely only 67 % of the 64-91 mm tracers were mobilized. The general trend of higher mobility for finer particles was consistent for four of the five sites, with Lens Creek being the exception. In Lens Creek 53 % of the coarsest tracers, 64-91 mm, were mobilized, while only 33% of the finest tracers, 22-32 mm, were mobilized. Since the overall mobility of tracers was much lower in Lens Creek than any of the other sites, it's possible that the effects of bed texture were more prominent in reducing particle entrainment. Previous research has indicated that smaller particles can become trapped in the interstices between larger stones, decreasing the likelihood that they are entrained during floods (Hassan and Bradley, 2017). This effect would be less significant when the bed is fully mobilized, which perhaps appears to be the case for Harris Creek and the San Juan River (Table 5.7).
Cumulative grain size distribution curves are presented for the immobile and mobile fractions of recovered tracers, as well as the tracers not recovered (Figure 5.17). Immobile tracers had the coarsest distribution of the three categories, mobile tracers had an intermediate grain size distribution, and the unrecovered tracers had the finest grain size distribution. This trend reiterates the fact that the finer particles were generally more easily entrained than the coarser particles. Since the unrecovered portion of the tracer population had the finest grain size distribution, it is most likely that they were transported farther downstream than was searched or that they were buried deeper than could be detected by the antenna. Overall, results are biased by the higher recovery of coarse grains.

Table 5.7. Mobility of tracer grain size classes.

<table>
<thead>
<tr>
<th>Grain Size (mm)</th>
<th>Bar 6</th>
<th>Bar 7</th>
<th>Tracer Mobility (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 - 32</td>
<td>90</td>
<td>93</td>
<td>33</td>
</tr>
<tr>
<td>32 - 45</td>
<td>89</td>
<td>96</td>
<td>50</td>
</tr>
<tr>
<td>45 - 64</td>
<td>84</td>
<td>71</td>
<td>40</td>
</tr>
<tr>
<td>64 - 90</td>
<td>75</td>
<td>74</td>
<td>53</td>
</tr>
</tbody>
</table>

Figure 5.17. Grain size distributions of mobile, immobile, and unrecovered tracers.
5.5.2 Grain Size Effects on Tracer Path Lengths

For tracers deployed on the mainstem (Bars 6, 7 and 15), median tracer path length was consistently inversely related to the tracer grain size class (Figure 5.18). The only exception to this trend was that the median path length for tracers larger than 90 mm deployed on Bar 6 was larger than the 45-64 and 64-90 mm tracers. However, only 12 tracers were used to calculate the > 90 mm median path length, so it is not expected to be a reliable representation of the average travel distance of particles of this size. The comparatively large median path length of these tracers is more likely a result of seeding position, since these particles were all positioned close to the thalweg initially, whereas other size classes were spread out across less active portions of the channel.

Of the three mainstem sites, Bar 6 tracers had the most similar median path length across grain sizes (Figure 5.18). The relative similarity in median path length for different sizes may be influenced by bar sedimentation at this location. The downstream growth of the bar head unit on Bar 6 was identified on the overall path length distribution as a location coincident with high tracer deposition (Figure 5.1). When the data is subdivided by grain size, it becomes apparent that tracers representative of the D$_{20}$-D$_{75}$ are clustering at the downstream extent of this feature (Figure 5.18) and no tracers exceeding 64 mm (i.e. > D$_{75}$) were transported beyond this distance. The growth of the bar head unit focuses at the bar apex (Figure 5.2), forcing the channel to meander around the bar. This combination of bar sedimentation and channel planform appears to restrict transport of particles to the bar tail leading to shorter median path lengths compared with the other mainstem bars where the channel is less sinuous and bar sedimentation is less extreme.

For Bar 7, tracers representative of the D$_{27}$-D$_{70}$ (i.e. 22-64 mm) had similar median path lengths, ranging from 168-224 m. However, tracers larger than 64 mm (i.e. > D$_{70}$) had a median path length of 73 m, as a large fraction of these coarser particles remained in the initial riffle in which they were seeded (Figure 5.18). The peak in tracer deposition at the bar apex, identified on the overall path length distribution (Figure 5.4), consists of the finer fraction of tracers ranging from 22-64 mm, as only one 64-90 mm tracer was transported beyond the bar apex.

Bar 15 had the largest differences in median path lengths between different grain sizes. Tracers representative of the D$_{40}$-D$_{54}$ (i.e. 22-45 mm) had median path lengths between 355 and 332 m, whereas tracers representative of the D$_{54}$-D$_{82}$ (i.e. 45-90 mm) had median path lengths between 176 and 91 m (Figure 5.18). The overall path length distribution for Bar 15 was described as multi-modal with four peaks in tracer deposition (Figure 5.7). When the data is subdivided by grain size, it appears that the initial short-
transport mode is largely composed of tracers between 45-90 mm. The second peak (~ 200 m), upstream of the bar apex, appears to have a range of tracer sizes from 22-64 mm, and the median path length for the 45-64 mm size class is located around this area. The third peak (~ 400 m), downstream of the bar apex, is mostly comprised of finer tracers, typically smaller than 45 mm (i.e. < D54). Similarly, the small peak in tracer concentration at the head of Bar 16 (and riffle with Bar 15) consists mainly of tracers smaller than 45 mm. Overall, there appears to be size-dependent path lengths associated with tracers deployed on Bar 15.

Harris Creek tracers coarser than 32 mm (i.e. > D32) had an inverse relationship between grain size class and median path length, however the 22-32 mm tracers were an anomaly to this trend (Figure 5.18). The low median path length for the 22-32 mm tracers was probably biased by the low recovery rate of this size fraction (33 %), and unrecovered tracers could well have been transported farther downstream than was searched. The cluster of tracers at the bar apex on the overall path length distribution appears to consist of all sizes of tracers (Figure 5.18).

Interpretation of size-dependent path lengths for Lens Creek tracers was limited by low tracer mobility rates (Table 5.7). Tracers representative of the D30-D84 (i.e. 32-90 mm) had similar median path lengths around 150 m, while the finer portion (i.e. <D30) had a median path length of 222 m (Figure 5.18). There does not appear to be consistent clustering of like-sized tracers at any particular locations in Lens Creek.

Overall, both mainstem and tributary tracers showed a general trend of increasing median path length with decreasing grain size (Figure 5.18). However, for Bar 6, the location with highest proportion of bar sedimentation and a more sinuous channel profile, median path lengths were relatively similar between grain sizes. A more detailed analysis of the grain size-path length relationship could be explored in the future by measuring the spatial variation in bed material grain sizes. This would allow a comparison to be made between locations where particular sizes of tracers are preferentially deposited with the grain size distribution of local bed material.
Figure 5.18. Tracer path lengths for each study site subdivided by grain size.
5.6 Effects of Seeding Position on Tracer Transport and Entrainment

In this study, tracers were seeded across channel cross-sections, such that individual tracers started at different elevations at or above the low-flow channel. In a previous tracer study conducted on a wandering gravel-bed channel, Liébault et al. (2012) found that tracers seeded in the low-flow channel travelled significantly longer distances (p<0.0001) than those starting on gravel bars, with median path lengths 15 to 30 times higher for tracers seeded in the low-flow channel. For this thesis, the starting position of tracers were assigned to a morphological unit (bar, pool, riffle, or bar-pool margin), the relative mobility of tracers within each unit was summarized (Tables 5.8 - 5.11), and the path length of tracers from each unit was graphed for each study site (Figure 5.21). No analysis was conducted for Lens Creek, because tracers were distributed across a plane-bed channel with little variation in elevation laterally.

For the Bar 6 launch line, tracers seeded in the pool had the highest median path length, followed by those seeded in the riffle (Figure 5.21a). Differences in tracer path lengths between pools and riffles may
be explained by variations in bed shear stress. Though no direct data on bed shear stress was measured, it is likely that shear stress was highest in pools during peak discharge events, as the water surface slope would be similar, but depth would be higher in pools than riffles during those periods. Tracers seeded on the tail of Bar 5 and the head of Bar 6 had similar median path lengths (85 and 88 m respectively), both lower than tracers placed closer to the thalweg (i.e. riffle/pool tracers). A group of 12 tracers were classified as starting on the bar-pool margin in 2016, and had the lowest median path length at 54 m.

For the Bar 7 launch line, tracers were either started on the tail of Bar X or the riffle between Bar X and Bar 7, none were placed at the head of Bar 7. Tracers starting in the riffle had a larger median path length (185 m) than those starting on Bar X (137 m) (Figure 5.21b). Conversely, the mobility of tracers seeded on the riffle was slightly lower than those seeded on Bar X. However, 95 % of the riffle-tracers were recovered, while only 66 % of the Bar X tracers were recovered. The mobility of Bar X tracers would likely have been lower with a higher recovery rate, as unrecovered tracers were probably buried at the launch line. Evidence of deposition on the tail of Bar X is shown in the DoD (Figure 5.26) and the 2015 and 2018 cross-sections (Figure 5.20).

For the Bar 15 launch line, tracers were spread across the head of Bar 15, a riffle, and the tail of Bar 14. Tracers seeded at the head of Bar 15 had the largest median path length, followed by riffle-tracers, and lastly those seeded on the tail of Bar 14. Similarly, the relative mobility of tracers was much higher for those placed at the head of Bar 15 (94 %), relative to the rest of the launch line (Table 5.10). These trends are also reflected by the overall changes to the channel, as the DoD of this area (Figure 5.27) shows that the tail of Bar 14 is growing, forcing the channel to erode the head of Bar 15, explaining the difference in tracer mobility across the launch line.
**Table 5.8.** Recovery rates and relative mobility of Bar 6 tracer stones summarized by the morphologic unit in which they were initially seeded.

<table>
<thead>
<tr>
<th>Seeding Location</th>
<th>n</th>
<th>n_r</th>
<th>r (%)</th>
<th>n_m</th>
<th>r_m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar 5</td>
<td>52</td>
<td>22</td>
<td>42</td>
<td>15</td>
<td>68</td>
</tr>
<tr>
<td>Bar 6</td>
<td>94</td>
<td>59</td>
<td>63</td>
<td>53</td>
<td>90</td>
</tr>
<tr>
<td>Pool</td>
<td>72</td>
<td>48</td>
<td>67</td>
<td>36</td>
<td>75</td>
</tr>
<tr>
<td>Bar-pool margin</td>
<td>28</td>
<td>13</td>
<td>46</td>
<td>12</td>
<td>92</td>
</tr>
<tr>
<td>Riffle</td>
<td>130</td>
<td>80</td>
<td>62</td>
<td>71</td>
<td>89</td>
</tr>
</tbody>
</table>

**Table 5.9.** Recovery rates and relative mobility of Bar 7 tracer stones summarized by the morphologic unit in which they were initially seeded.

<table>
<thead>
<tr>
<th>Seeding Location</th>
<th>n</th>
<th>n_r</th>
<th>r (%)</th>
<th>n_m</th>
<th>r_m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar X</td>
<td>208</td>
<td>138</td>
<td>66</td>
<td>107</td>
<td>78</td>
</tr>
<tr>
<td>Riffle</td>
<td>55</td>
<td>52</td>
<td>95</td>
<td>38</td>
<td>73</td>
</tr>
</tbody>
</table>

**Table 5.10.** Recovery rates and relative mobility of Bar 15 tracer stones summarized by the morphologic unit in which they were initially seeded.

<table>
<thead>
<tr>
<th>Seeding Location</th>
<th>n</th>
<th>n_r</th>
<th>r (%)</th>
<th>n_m</th>
<th>r_m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar 14</td>
<td>52</td>
<td>33</td>
<td>63</td>
<td>21</td>
<td>64</td>
</tr>
<tr>
<td>Bar 15</td>
<td>50</td>
<td>33</td>
<td>66</td>
<td>31</td>
<td>94</td>
</tr>
<tr>
<td>Riffle</td>
<td>168</td>
<td>116</td>
<td>69</td>
<td>75</td>
<td>65</td>
</tr>
</tbody>
</table>

**Table 5.11.** Recovery rates and relative mobility of Harris Creek tracer stones summarized by the morphologic unit in which they were initially seeded.

<table>
<thead>
<tr>
<th>Seeding Location</th>
<th>n</th>
<th>n_r</th>
<th>r (%)</th>
<th>n_m</th>
<th>r_m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar</td>
<td>107</td>
<td>77</td>
<td>72</td>
<td>69</td>
<td>90</td>
</tr>
<tr>
<td>Pool</td>
<td>83</td>
<td>38</td>
<td>46</td>
<td>31</td>
<td>82</td>
</tr>
<tr>
<td>Bar-pool margin</td>
<td>52</td>
<td>31</td>
<td>60</td>
<td>27</td>
<td>87</td>
</tr>
</tbody>
</table>

*Note: Number of tracers recorded in these tables only includes those found in the first survey after they were deployed (i.e. tracers found after two or three years were removed). Also, data is aggregated across all years.*
Figure 5.21. Tracer path lengths subdivided by initial seeding location for (a) Bar 6 tracers, (b) Bar 7 tracers, (c) Bar 15 tracers and (d) Harris Creek tracers.
For the Harris Creek launch line, tracers seeded in the pool had a larger median path length than those seeded on the bar (Figure 5.21d). Tracers seeded on the margin between the pool and the bar had the highest median path length overall at 159 m. While the mobility of tracers was high across the launch line, those seeded on the bar were slightly more mobile than those seeded in the pool, though this may just be a result of the low recovery rate for pool-tracers (Table 5.11).

5.7 Active Layer Depth and Tracer Burial

While not the primary focus of this study, the tracer data collected on the San Juan River provides insight into the depth of the active layer in a wandering gravel-bed channel. A summary of tracer burial data for each location is presented in Table 5.12. Note that median burial depths are presented here, rather than means, because any tracers buried deeper than 50 cm were not physically dug up, and thus the absolute burial depth was unknown. These data are still included as ranked data to determine median burial depths. Tracers that were detected in deep pools could not be physically recovered and were removed from burial depth analysis. There was no observed relationship between grain size and median burial depth for tracers deployed on the mainstem (Figure 5.22).

Of the mainstem sites, Bar 6 had the greatest median burial depths of tracers and the highest relative fraction of tracers buried. Bar 15 had the lowest proportion of tracers buried and the lowest median burial depth, whilst Bar 7 tracers had intermediate burial depths between the two (Table 5.12). Overall, 76% of tracers recovered in the San Juan River were buried, with a median depth of 14 cm. On Harris Creek, 89
% of recovered tracers were buried, with a median burial depth of 19 cm. The high burial rate on Harris Creek may indicate that unrecovered tracers were also buried, potentially deeper than could be detected by the antennas, indicative of sedimentation from upstream delivery. Just 71% of Lens Creek tracers were buried, with a median burial depth of 10 cm (Table 5.12).

<table>
<thead>
<tr>
<th>Location</th>
<th>(n_{\text{buried}})</th>
<th>(n_{\text{surface}})</th>
<th>(r_{\text{buried}})</th>
<th>Median Burial Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar 6</td>
<td>186</td>
<td>38</td>
<td>0.83</td>
<td>21.5</td>
</tr>
<tr>
<td>Bar 7</td>
<td>124</td>
<td>47</td>
<td>0.73</td>
<td>12.5</td>
</tr>
<tr>
<td>Bar 15</td>
<td>106</td>
<td>46</td>
<td>0.70</td>
<td>7</td>
</tr>
<tr>
<td>San Juan Combined</td>
<td>416</td>
<td>131</td>
<td>0.76</td>
<td>14</td>
</tr>
<tr>
<td>Harris</td>
<td>110</td>
<td>14</td>
<td>0.89</td>
<td>19</td>
</tr>
<tr>
<td>Lens</td>
<td>108</td>
<td>44</td>
<td>0.71</td>
<td>10</td>
</tr>
</tbody>
</table>

NOTE: \(r_{\text{buried}}\) is the fraction of recovered tracers that were buried.

The distribution of tracer burial depths for each site are presented in Figure 5.23 to provide insight into active layer depths. For Bar 6 tracers were relatively evenly buried across a range of depths up to 35 cm, with an additional 29% buried deeper than 50 cm. Only 7% were found within 5 cm of the surface. Burial depths were generally lower on Bar 7, with 67% of recovered within 25 cm of the surface, though an additional 26% were deeper than 50 cm. Bar 15 displayed the lowest burial depths on the mainstem, with 29% recovered within 5 cm of the surface, and 74% within 15 cm. Harris Creek displayed a range of tracer burial depths up to 30 cm, with 23% of tracers buried deeper than 50 cm. Burial was substantially lower on Lens Creek, with 27% of tracers recovered within 5 cm of the surface and 72% within 15 cm. Overall, Bars 6, 7 and Harris Creek appear to have high tracer burial depths indicative of a deep active layer, whereas Bar 15 and Lens Creek tracers were generally deposited at shallower depths.

The traditional view of an active layer of uniform thickness, typically less than twice the \(D_{90}\) (Hassan and Bradley, 2017), is not reflected by tracer burial depths in this study. The values for \(2D_{90}\) are depicted as red lines on the tracer burial distributions in Figure 5.23. For all five sites, some fraction of the tracer population were recovered at depths exceeding \(2D_{90}\). Deep tracer burial was most significant for Bars 6, 7 and Harris Creek as roughly 55, 33, and 39% of buried tracers were recovered deeper than \(2D_{90}\) respectively. This indicates that particle exchange during bedload transport in these channels operates at depths beyond a thin bed surface layer.
Figure 5.23. Distribution of tracer burial depths for (a) Bar 6, (b) Bar 7, (c) Bar 15, (d) Harris Creek, and (e) Lens Creek. Note that tracers recovered at the surface are not included in these figures. Red lines represent 2\*D_{90} of the local bed material.
Tracer burial data was also summarized by year to assess annual differences (Table 5.13). Only data for tracers seeded on the mainstem were included, since no tracers were seeded on Harris or Lens Creek in 2015 and including them would make the data non-comparable. The largest fraction of tracers buried, and the greatest median burial depth, occurred for tracers deployed in 2015, followed by those deployed in 2017 and lastly those deployed in 2016. This pattern follows the trend in peak discharge for each tracer deployment year (Table 5.3). The high burial rate for tracers deployed in 2015 was also influenced by the fact that only 33 were recovered after one year, with the remainder recovered after two or three years, providing a longer period for vertical mixing to occur when compared to the most recently deployed tracers that were recovered after just one year. Tracers seeded in 2016 had a much lower burial rate (68 %) and median burial depth (9 cm) than the other two years. Both the peak discharge and excess flow volume in the 2016-17 winter was much lower than the other seasons (Table 5.3), evidence that these variables influence individual particle burial. The fact that tracer burial depths are correlated with peak discharge is a valuable result since it indicates indirectly which years had higher morphological change, a result which cannot be determined from the GCD analysis since LiDAR surveys were not conducted annually.

<table>
<thead>
<tr>
<th>Launch Year</th>
<th>n_{buried}</th>
<th>n_{surface}</th>
<th>n_{buried}</th>
<th>Median Burial Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>63</td>
<td>8</td>
<td>0.89</td>
<td>24</td>
</tr>
<tr>
<td>2016</td>
<td>267</td>
<td>126</td>
<td>0.68</td>
<td>9</td>
</tr>
<tr>
<td>2017</td>
<td>304</td>
<td>55</td>
<td>0.85</td>
<td>18</td>
</tr>
<tr>
<td>Combined</td>
<td>634</td>
<td>189</td>
<td>0.77</td>
<td>14</td>
</tr>
</tbody>
</table>

5.8 Geomorphic Change Detection Analysis

One of the main objectives of this research was to highlight the reciprocal relationship between channel morphology and bedload transport. While prior sections of this chapter have focused upon individual particle movement, this section will present results for the overall changes in channel topography and link these changes with particle movement and burial. Geomorphic change detection analysis was performed to produce DoDs for each of the tracer study sites. The final position of buried tracers was overlaid on top of the DoDs to contextualize the location and magnitude of particle burial with overall changes in channel topography.
DoDs were generated using probabilistic thresholding at the 80 and 95 % confidence intervals. A comparison of DoDs at the two confidence intervals is presented in Figure 5.24 for the channel reach encompassing Bars 6 and 7. The two DoDs were similar, with the primary difference being that the 95 % confidence interval DoD thresholded out real change along the eroding banks opposite both Bars 6 and 7. Upon reviewing the DoDs for each site, the 80 % confidence interval outputs did a better job at capturing real geomorphic change, and the 95 % confidence interval DoDs were deemed overly conservative. Therefore, further results presented in this thesis are for the 80 % confidence interval DoDs only.

![Figure 5.24. Comparison of DoDs for the Bar 6-7 reach, thresholded at the 80 and 95 % confidence intervals. The solid black line depicts the processing extent used in change detection analysis.](image)

5.8.1 Bars 6 and 7

The DoD for the channel reach encompassing Bars 6 and 7 had a total volume of deposition of $21,536 \pm 5,176$ m$^3$ and a total volume of erosion of $16,590 \pm 6,315$ m$^3$ (Table 5.14). Volumetric changes were segregated by the change in land cover (i.e. change between gravel, water, or vegetation) and summarized in Table 5.14. Bank erosion opposite both Bars 6 and 7 (i.e. a change from vegetation to water in imagery)
accounted for 72% of the total erosion for this reach. This is significant, since the banks are primarily composed of fine sand and silt, thus bank erosion is supplying finer material than is typically found on the channel bed. The second largest source of erosion was in areas changing from gravel to water (14% of the total erosion), but this was not exclusively real geomorphic change as it was partially influenced by the higher-stage in 2018. Erosion on bars (i.e. areas that remained classified as gravel between 2015 and 2018) accounted for 12% of the total volume of erosion. This included the migrating bedload sheet at the head of Bar 6, erosion at the head of Bar 7, and pools scoured out at the tail of Bar 6 (Figures 5.25 and 5.26). Vertical accretion on areas that remained classified as gravel through 2015-2018 accounted for 53% of the total volume of deposition, and areas changing from water to gravel (i.e. bar margins) accounted for 36% of the total volume of deposition. Deposition on bar surfaces occurred from the bar apex down to the tail, with maximum deposition focused at the apex of Bar 6 due to the migration of the downstream end of the gravel sheet (Figures 5.25 and 5.26). There was also deposition at the upstream end of Bar 6, inside of the migrating bedload sheet, evidence that some fraction of the sediment load is routed along the inside of the bar. Additionally, the small point bar, Bar X, has migrated around the meander between Bars 6 and 7, causing net deposition across most of the Bar 7 launch line from 2015 to 2018. This may be causing the relatively low recovery rate for tracers on this portion of the Bar 7 launch line (Table 5.9), since some tracers were likely buried in the bar tail.

For Bar 6, 37% of buried tracers were found in net depositional areas, 3% were found in net erosional areas, and 60% were found in areas of indeterminate change (Table 5.15). High tracer burial in net depositional areas relative to net erosional areas aligns with the earlier analysis indicating that the Bar 6 tracer population was preferentially recovered in depositional environments (e.g. riffles and bars), especially those that moved a substantial distance. The high fraction of tracers deposited in areas of indeterminate change mainly reflects those deposited in the riffle between Bars 5 and 6, where the LiDAR was unable to reach the bed surface. The concentration of tracers buried in this riffle suggests that it probably aggraded between 2015 and 2018, though tracer burial was generally less than 10 cm. A large cluster of tracers were deeply buried (> 40 cm) at or downstream of the bar apex, around the area of maximum deposition on the DoD. Note that the deep burial of these particles would constrain travel distance as once they are buried they become shielded from the flow until a discharge event occurs capable of altering the bar and remobilizing sediment buried at this depth. In other words, the mobility of individual grains is tied directly to the bar dynamics. A cluster of buried tracers also accumulated at the bar tail, mainly an area of deposition, though there was an elongated patch of erosion ending at a scour pool on the bar tail. Bar 6 imagery (Figure 5.2) shows that the river avulses into two channels around the
tail of Bar 6, one that flows around the bar edge, and one that flows over the bar top creating the scour seen on the DoD. No buried tracers were recovered in the channel that flows along the left bank around the bar tail, but the cluster of tracers on the bar tail surface appears to line up with the flow path of the bar-top channel.

Table 5.14. Volumetric budget segregation results for the Bars 6-7 DoD.

<table>
<thead>
<tr>
<th></th>
<th>Total Volume of Surface Lowering (m$^3$)</th>
<th>Total Volume of Surface Raising (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Raw</td>
<td>Thresholded</td>
</tr>
<tr>
<td>Gravel to Gravel</td>
<td>2,302</td>
<td>1,960</td>
</tr>
<tr>
<td>Gravel to Vegetation</td>
<td>47</td>
<td>16</td>
</tr>
<tr>
<td>Gravel to Water</td>
<td>2,806</td>
<td>2,255</td>
</tr>
<tr>
<td>Vegetation to Gravel</td>
<td>491</td>
<td>468</td>
</tr>
<tr>
<td>Vegetation to Vegetation</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vegetation to Water</td>
<td>14,286</td>
<td>11,889</td>
</tr>
<tr>
<td>Water to Gravel</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>Water to Vegetation</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Water to Water</td>
<td>2,157</td>
<td>0</td>
</tr>
<tr>
<td>Total of All Compared</td>
<td>22,112</td>
<td>16,590</td>
</tr>
</tbody>
</table>

NOTE: Changes from gravel to gravel reflect vertical accretion on bar surfaces, water to gravel changes indicate lateral accretion of bars, vegetation to water changes indicate bank erosion, and gravel to water changes are a mixed signal of bar erosion and error caused by stage differences.
Bar 7 tracers were buried primarily in net depositional areas (58%), with 8% buried in net erosional areas, and 34% buried in areas of indeterminate change (Table 5.15). Again, this result aligns with the earlier analysis that indicated higher recovery of tracers on bars and in riffles relative to pools for Bar 7. Burial depths were small for tracers in net erosional areas. The maximum burial of tracers (> 50 cm) was focused at the left side of the launch line, as Bar X migrated through this area, burying tracers and rendering them immobile. High burial depths also occurred for a cluster of tracers around the apex of Bar 7. Downstream of the bar apex, tracer burial was minimal with burial depths less than 10 cm.

**Figure 5.25. Bar 6 DoD and the position of buried tracers**
Figure 5.26. Bar 7 DoD and the position of buried tracers

Table 5.15. Summary of tracer recovery rates within areas of erosion, deposition, or indeterminate change.

<table>
<thead>
<tr>
<th>Location</th>
<th>$r_{\text{erosion}}$ (%)</th>
<th>$r_{\text{deposition}}$ (%)</th>
<th>$r_{\text{unknown}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar 6</td>
<td>3</td>
<td>37</td>
<td>60</td>
</tr>
<tr>
<td>Bar 7</td>
<td>8</td>
<td>58</td>
<td>34</td>
</tr>
<tr>
<td>Bar 15</td>
<td>5</td>
<td>11</td>
<td>85</td>
</tr>
<tr>
<td>Harris</td>
<td>2</td>
<td>11</td>
<td>88</td>
</tr>
<tr>
<td>Lens</td>
<td>1</td>
<td>1</td>
<td>98</td>
</tr>
<tr>
<td>Overall</td>
<td>4</td>
<td>26</td>
<td>70</td>
</tr>
</tbody>
</table>
5.8.2 Bar 15

The Bar 15 DoD had a total volume of deposition of 8,960 ± 2,130 m$^3$ and a total volume of erosion of 4,159 ± 1,473 m$^3$ (Table 5.16). Bank erosion opposite Bar 15 (and a small volume opposite Bar 16) accounted for 42 % of the total volume of erosion (Table 5.16). Erosion at the head of Bar 15, and to a lesser extent the head of Bar 16, accounted for 31 % of the total volume of erosion. Change from gravel to water accounted for 15 % of the total erosion, and again was not considered to be a reliable indicator of real change due to stage differences. Areas changing from vegetation to gravel resulted in 11 % of the total erosion. Vertical accretion on bars accounted for 75 % of the total volume of deposition, while 11 % of the total volume of deposition occurred at bar margins. However, based upon field observations, and on the clustering of tracers along the Bar 15 margin, it’s likely that the estimate of deposition along the margin is conservative, and in-channel topographic data is needed to monitor changes in these areas. Deposition occurred across the entire surface of Bars 15 and 16 from the mid-bar down to the tail as both bars have migrated downstream between 2015 and 2018. Similarly, the tail of Bar 14 migrated downstream, resulting in net deposition over part of the Bar 15 tracer launch line. Also, there was deposition at the top of Bar 15 along the inside of the bar where it is attached to the bank, suggesting that some fraction of the sediment load is transferred along the inside of the bar.

Bar 15 tracers were buried primarily in areas of indeterminate change (85 %), with 11 % found in net depositional areas, and 5 % found in net erosional areas (Table 5.16). This pattern emerged because of the immobile mode of tracers clustering in the riffle between Bars 15 and 16 (an area of indeterminate change), and because of tracer burial focused along the bar-pool margin (Figure 5.27). Few tracers were buried on the bar surface, despite the vertical accretion across the bar surface from the bar apex to the tail. Tracer burial depths were highest at the launch line, with only moderate to low burial depths for tracers deposited on the lower half of Bar 15.
Table 5.16. Volumetric budget segregation results for the Bar 15 DoD.

<table>
<thead>
<tr>
<th></th>
<th>Total Volume of Surface Lowering (m³)</th>
<th>Total Volume of Surface Raising (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Raw</td>
<td>Thresholded</td>
</tr>
<tr>
<td>Gravel to Gravel</td>
<td>1,552</td>
<td>1,270</td>
</tr>
<tr>
<td>Gravel to Vegetation</td>
<td>140</td>
<td>80</td>
</tr>
<tr>
<td>Gravel to Water</td>
<td>774</td>
<td>610</td>
</tr>
<tr>
<td>Vegetation to Gravel</td>
<td>476</td>
<td>466</td>
</tr>
<tr>
<td>Vegetation to Vegetation</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vegetation to Water</td>
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<td>1,733</td>
</tr>
<tr>
<td>Water to Gravel</td>
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<td>0</td>
</tr>
<tr>
<td>Water to Vegetation</td>
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<td>1</td>
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<tr>
<td>Water to Water</td>
<td>278</td>
<td>0</td>
</tr>
<tr>
<td>Total of All Compared</td>
<td>5,567</td>
<td>4,159</td>
</tr>
</tbody>
</table>

NOTE: Changes from gravel to gravel reflect vertical accretion on bar surfaces, water to gravel changes indicate lateral accretion of bars, vegetation to water changes indicate bank erosion, and gravel to water changes are a mixed signal of bar erosion and error caused by stage differences.

Figure 5.27. Bar 15 DoD and the position of buried tracers
5.8.3 Harris Creek
The DoD for the section of Harris Creek from the bridge to about 500 m downstream of the tracer launch line is presented in Figure 5.28. This reach had 1,492 ± 455 m$^3$ of total erosion, and 3,173 ± 892 m$^3$ of total deposition (Table 5.17). Based on the volumetric budget segregation (Table 5.17), only 34 % of the total erosion occurred on bars, and 56 % occurred on areas that changed from gravel to water and thus cannot reliably be considered real geomorphic change. Bank erosion was a far less important process in this section of Harris Creek, when compared to sites on the San Juan River, accounting for just 5 % of the total volume of erosion. Vertical accretion on bars accounted for 66 % of the total deposition, while 24 % occurred on areas changing from gravel to water. The latter changes were interpreted as interpolation error in the 2018 DEM because areas changing from gravel to water would be expected to be net erosional. Most deposition occurred on the bar along the left bank extending about 450 m downstream of the launch line, with deposition focused on the mid-bar and tail. The bar head shows areas of erosion and deposition, suggesting that during higher discharges, flow is spread across multiple channels both around and over the bar top (Figure 5.28).

Harris Creek tracers were buried primarily in areas of indeterminate change (88 %) due to the limited geomorphic change detected in Harris Creek. Of the fraction recovered in areas of change, 11 % were found in net depositional areas, and 2 % were found in net erosional areas (Table 5.15). The lack of topographic change captured in Harris Creek limited analysis linking bedload path lengths with morphologic changes. From Figure 5.28, buried tracers were preferentially located on the left side of the channel, where a 500 m long gravel bar is located. There was a tight cluster of tracers with high burial depths located about 200 m downstream of the launch line at the bar apex (Figure 5.28). This area was classified as indeterminate change on the DoD but is adjacent to an erosional patch on the left side of the channel. There were no clear morphological features linked with this cluster of buried tracers. In-channel topographic data would be required to detect net vertical changes here.
Table 5.17. Volumetric budget segregation results for the Harris Creek DoD.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Total Volume of Surface Lowering (m³)</th>
<th>Total Volume of Surface Raising (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Raw</td>
<td>Thresholded</td>
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<tr>
<td>Gravel to Gravel</td>
<td>637</td>
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<td>Gravel to Vegetation</td>
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<td>Vegetation to Vegetation</td>
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<td>0</td>
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<tr>
<td>Vegetation to Water</td>
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<td>68</td>
</tr>
<tr>
<td>Water to Gravel</td>
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<td>4</td>
</tr>
<tr>
<td>Water to Vegetation</td>
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<td>6</td>
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<tr>
<td>Water to Water</td>
<td>2,569</td>
<td>0</td>
</tr>
<tr>
<td>Total of All Compared</td>
<td>4,694</td>
<td>1,492</td>
</tr>
</tbody>
</table>

NOTE: Changes from gravel to gravel reflect vertical accretion on bar surfaces, water to gravel changes indicate lateral accretion of bars, vegetation to water changes indicate bank erosion, and gravel to water changes are a mixed signal of bar erosion and error caused by stage differences.

Figure 5.28. Harris Creek DoD and the position of buried tracers. Note that some tracers were exported downstream of this area but were not included in this figure since the DoD does not extend that far downstream.
5.8.4 Lens Creek

The DoD for Lens Creek is presented in Figure 5.29. GCD analysis was extremely restricted for Lens Creek since the channel was mostly covered by water and/or overhanging trees during the 2018 LiDAR survey, leading to very low or non-existent point densities across the channel. From the change that was detected, this section of Lens Creek had $249 \pm 82 \text{ m}^3$ of total erosion, and $393 \pm 155 \text{ m}^3$ of total deposition. The two main areas of deposition were at the tails of the two bars in this reach. Some minor deposition was detected at or downstream of the tracer launch line. The main area of erosion was at the head of the bar attached to the left bank. No volumetric budget analysis is presented due to the small volumetric changes and high uncertainty in the results.

![Figure 5.29. Lens Creek DoD and the position of buried tracers](image)

Due to the lack of real geomorphic change detected in the Lens Creek DoD, no links between tracer burial and morphologic changes were established. Overall, burial in Lens Creek was low, with most tracers found within 10 cm of the bed surface. Tracer burial appears to be dispersed across the channel, with no clear
clustering of high burial depths in any one location. The highest burial depths in general occurred for immobile tracers recovered along the launch line (Figure 5.29).

5.8.5 Active Layer Dimensions

Further insights in the depth of the active layer can be garnered through analysis of vertical elevation changes from DoDs. The volume of change from DoDs was plotted as a function of elevation change for Bars 6 and 7, Bar 15, and Harris Creek in Figure 5.30. For the Bars 6 and 7 DoD, the maximum volume of deposition was associated with elevation changes of around 0.6 - 0.7 m (Figure 5.30a). This was reflected in tracer burial depths, as 29 and 26 % of tracers were buried deeper than 0.5 m for Bars 6 and 7 respectively. The maximum volume of deposition for Bar 15 was associated with elevation changes around 0.2 – 0.3 m (Figure 5.30b). This also lines up with tracer burial depth results, as 94 % of buried tracers on Bar 15 were found within 0.3 m of the surface. On Harris Creek, the maximum volume of deposition was associated with elevation changes around 0.2 m (Figure 5.30c). However, just 21 % of buried tracers on Harris Creek were found within 0.1 m of the surface, with 23 % were buried deeper than 0.5 m. Overall, tracer burial depths were on the scale of morphological changes observed from DoDs. Further, the range of elevation changes shown in Figure 5.30, and the distribution of tracer burial depths in Figure 5.23, confirm that a spatially variable morphologically active layer is an appropriate concept in which to discuss bedload transport for dynamic gravel-bed channels. It is worth re-iterating the larger point here, that the volume of erosion from Figure 5.30, when combined with the path lengths (per unit time) obtained via the tracer dataset and scaled by the reach-length can provide rough numbers for the morphological bedload transport rate in each of these channel reaches (Ashmore and Church, 1998; Vericat et al., 2017). However, in-channel topographic data would be required to calculate a more accurate and complete bedload flux.

Interestingly, the DoDs for Bars 6, 7 and 15 reaches were all net depositional overall. There are several possibilities that may explain this. For one, the entire channel area wasn’t surveyed, and changes occurring in the deep sections of channel, where erosion would be expected to occur, weren’t captured by the DoDs. If bathymetric data were available, it is possible that changes occurring in-channel would have offset the net deposition observed in Figure 5.30, and these reaches may actually be in equilibrium. Another possibility is that these reaches are actually net depositional, but that if the DoD had been extended farther up or downstream, then they would be in equilibrium. In other words, the net deposition observed was an artefact of the artificially defined survey extent but does not reflect channel sedimentation for the alluvial reach as a whole. A third explanation is that the channel is net depositional,
and high sediment supply is still being delivered to the alluvial reach and stored primarily in bars. Based on the analysis in this study, it is unclear which of these situations is real, and more complete topographic surveying would be required to resolve this.

Figure 5.30. Volumetric changes from DoDs as a function of changes in elevation for (a) Bars 6 and 7, (b) Bar 15, and (c) Harris Creek.
5.8.6 Summary of Geomorphic Change Detection

Between 2015 and 2018, gravel bars on the San Juan River displayed patterns of erosion at the bar head with vertical accretion from the bar apex down to the tail, reflective of downstream bar migration. While Bars 7 and 15 displayed minor lateral accretion at or downstream of the bar apex, this process appears to be most significant on Bar 6. In response to the bars building out laterally, the channel has compensated via erosion of the opposite bank. Again, this process is most extreme opposite Bar 6. Bank erosion is supplying finer material to the channel than found on the bed surface, altering the sediment composition downstream. The extent of bank erosion is also reflected in the channel sinuosity for each of these reaches, as the channel is most sinuous around Bar 6 (where bank erosion appears the most rapid) but follows a straighter profile around Bars 7 and 15. Some fraction of the sediment load is also routed along this inside of bars, particularly at the head of Bar 6. There appear to be scour pools developing at the tails of Bars 6 and 7 on the inside of the bars, evidence that during peak floods the river avulses at the bar tail with a second channel across the surface of the bar. Overall, the river displayed lateral instability, and downstream migration of bars and meanders, changes that were generally reflected in patterns of tracer burial. Tracers seeded on bar tails tended towards immobility and/or short displacements, due to burial caused by vertical accretion of the bar tail. Of the tracers that travelled longer distances, burial focused at the apex of Bars 6 and 7, and downstream of the apex for Bar 15. Tracer burial depths were typically highest on Bar 6 and lowest on Bar 15, again reflective of the bar dynamics.

On Harris and Lens Creek, less morphological change was observed than on the mainstem. Both reaches are confined to a relatively straight channel and appear much more laterally stable than the San Juan River. Lateral accretion of bars and bank erosion were not identified as significant processes in these channels. Of the two, more substantial changes were observed on Harris Creek. The largest bar in the Harris Creek reach, along the left bank, showed a similar pattern of erosion and deposition as mainstem bars, with erosion at the bar head and deposition on the surface of the bar from the apex to the tail. The river also appears to braid around the head of this bar, as linear patches of scour and deposition were observed on the DoD at the bar head. Analysis of the tributary channels was quite limited since water levels were high in 2018, and the narrower channel widths were partially obscured by overhanging riparian vegetation, especially in Lens Creek. The lack of observed changes in Lens Creek is supported however by the relative immobility of tracers, indicating that bedload transport, and thus changes in channel morphology, were likely very low during this period.
5.9 Long-term Changes in Channel Morphology

In this thesis, results from particle movement were contextualized with net changes in channel morphology between 2015 and 2018. However, this can be explored further, to assess how annual particle transport relates to longer-term changes in the channel. Channel boundaries from 1995 to 2018, originally presented in Figure 3.10, have been plotted over the 2015-18 DoD and buried tracer locations in Figure 5.31. This allowed a comparison of the long-term changes in channel width with shorter-term volumetric changes from DoDs, and ultimately with the deposition and burial of individual particles.

The most extreme changes in channel planform is the widening of the channel around Bar 6 due to the retreat of the outer bank opposite the bar (Figure 5.31a). Erosion of the bank opposite Bar 6 was also observed in the 2015-18 DoD. This appears to be a direct response to the expansion and lateral accretion around the apex of Bar 6. Channel widening and bank erosion opposite the bar apex are also observed along Bar 7 (Figure 5.31b). This provides evidence that the preferential deposition and burial of tracers around the bar apex observed on an annual timescale may perhaps be a trend persistent over longer time-scales as the bar continues to grow. This also aligns with the description of bar development and lateral instability documented in other wandering gravel-bed channels (Church and Rice, 2009; Rice et al., 2009).

Changes in the channel boundaries around Bar 15 were less severe than changes observed around Bars 6 and 7 (Figure 5.31c). The relatively low rate of bank retreat opposite Bar 15 (compared to Bars 6 and 7) is reflected by the low magnitude of change observed on the Bar 15 DoD. In total, there was $8,960 \pm 2,130 \text{ m}^3$ of deposition in the Bar 15 DoD, of which just 11% was ascribed to lateral accretion. The primary mode of deposition from the DoD was vertical accretion of the bar surface. If the bar is mainly being built vertically as opposed to laterally, then the channel is not forced towards the outer bank causing channel widening. Interestingly, tracer deposition focused along the length of the Bar 15-pool margin, suggesting that the bar is primarily being built out laterally. However, tracer burial depths were particularly shallow on Bar 15 with 29% found within 5 cm of the surface. This may indicate that particles are being routed along the bar-pool margin around Bar 15 but are not trapped and buried in this area, leaving them exposed to subsequent floods and more likely to be re-mobilized and exported out of the area entirely. Overall, this section of the river appears less morphologically active than at Bars 6 and 7.
Figure 5.31. Changes in channel boundaries from 1995 to 2018, overlaid on top of 2015-2018 DoDs and buried tracer positions for (a) Bar 6, (b) Bar 7, and (c) Bar 15. Black arrows depict the primary direction of change(s) over time.
5.10 Summary of Results

In summary, the tracer experiment provided valuable information on the entrainment, transport, and deposition of individual particles, ranging from 22-128 mm, at three separate locations along the lower San Juan River as well as a single location on both Lens and Harris Creeks. This dataset was coupled with geomorphic change detection analysis, to contextualize the movement and burial of particles with overall changes in channel morphology for each of the sites, addressing the main research question. Key results from this chapter are outlined in the following section.

A recovery rate of 72% was achieved across all sites with consistently higher recovery of coarser tracers relative to finer ones. Tracer path length distributions for all sites displayed a short-transport mode, reflective of intrabedform transport as particles remained within the riffle/bar/pool in which they were initially seeded. The path length distribution for both mainstem and Harris Creek tracers displayed distinct peaks in tracer deposition at or just downstream of bar apexes and at downstream riffles. The deposition of tracers at bar apexes was generally along the bar-pool margin, reflective of lateral bar development. On the mainstem, tracers were rarely transported farther than the downstream extent of the bar in which they were seeded, even two or three years after deployment.

The relationship between tracer mobility and transport with discharge, grain size, and seeding position were examined. Both the relative mobility and median path length of tracers was higher during years with higher peak discharge, excess flow volume and the number of threshold events. No correlation was observed with the total annual flow volume (i.e. including discharge below the threshold for gravel entrainment). Median path lengths were generally inversely related with grain size, however, tracers seeded at Bar 6 had relatively similar path lengths for different grain sizes, perhaps due to deep burial at the bar apex limiting transport of all sizes to the bar tail. Tracer mobility also increased with decreasing grain size. Tracers seeded closer to the thalweg consistently had higher mobility and median path lengths compared with those seeded farther away from the thalweg. Tracers seeded on bar tails were often rendered immobile due to deposition on bar tails as they migrated downstream.

Tracer burial depths were summarized and differences annually and between sites were examined. For the San Juan River, both the relative fraction of tracers that were buried and the median burial depth of said particles correlated with peak discharge and excess flow volume. There was no evidence of tracer burial depths varying by grain size for this dataset. Differences in tracer burial were observed on a site by site basis. Bars 6, 7 and Harris Creek displayed high burial depths, with over 25% of tracers buried deeper than 50 cm. Conversely, Bar 15 and Lens Creek tracers tended towards deposition at shallower depths.
indicating that the active layer depth is probably shallower at these sites. These results generally agree with morphological changes from DoDs between 2015 and 2018. Net deposition on Bars 6 and 7 was high, especially at the apex of Bar 6, resulting from the migration of a coarse bedload sheet. Vertical accretion on Bar 15 was less than on Bars 6 and 7, matching the shallow burial depth of tracers. The distribution of tracers on Harris Creek displayed relatively high burial depths, contrary to the low volume of net deposition in the DoD. The Lens Creek DoD showed very minor morphological changes (largely due to sources of error associated with topographic surveys), and shallow tracer burial.

Of the reaches analysed within the San Juan River, the primary source of erosion was bank erosion followed by erosion at bar heads. Vertical accretion tended to focus at the bar apex down to the bar tail, reflective of bars migrating downstream. Lateral accretion occurred at or just downstream of the bar apex. Net changes in channel morphology were used to contextualize results from the tracer data. Buried tracers tended to accumulate in net depositional areas on DoDs, or more commonly in areas of indeterminate change, while rarely ending up in net erosional areas. Areas of indeterminate change are distinct from areas of no change and were mainly a result of the absence or poor-quality of topographic data. As such, the accumulation of tracers in areas of indeterminate change was mainly attributed to tracer clustering in riffles and along bar-pool margins, regions that often lacked topographic data. These areas would likely have been net depositional had bathymetric data been available. Overall, morphologic changes on the San Juan River was well reflected in the deposition and burial of tracers. Further, the processes of bar expansion and bank erosion were reflected over the long-term by the lateral instability and channel widening observed between 1995 and 2018.
Chapter 6: Discussion

In this chapter the path length distributions reported in this thesis will be compared with results from the literature, along with discussion of the broader implications of these results for linking bedload sediment transport and changes in channel morphology in wandering channels (Section 6.1). Further, the effects of discharge and grain size on tracer transport will be compared with other results in the literature (Section 6.2). A review of tracer recovery rates and the technical details of the tracer experiment are discussed in Section 6.3, with recommendations for how to optimize field campaigns for future RFID tracking experiments in wandering channels. Section 6.4 for will provide a brief review of topographic surveying in this study and potential improvements. The active layer depth and tracer burial is discussed in Section 6.5. Finally, the implications for restoration work in the San Juan River Watershed, and for similar rivers, is discussed in Section 6.6.

6.1 Path Length Distributions

The San Juan River tracer path length distributions point towards the underlying relationship between the transport and deposition of individual particles and the morphological ‘style’ of the channel. Meaning that the wandering habit exhibited by the San Juan River, caused primarily by bank erosion in response to the lateral development of bars, is tied to the transport and deposition of individual grains. Tracer path length distributions for the San Juan River exhibited bi- and multi-modal distributions. A short-transport mode was persistent across sites, with downstream modes associated with the bar apex region and to a lesser extent riffles. The spatial distribution of tracers highlighted the tendency for tracers to accumulate on the bar-pool margin at or downstream of the bar apex, indicative of lateral bar development. These observations aligned with the spatial patterns of erosion and deposition in the 2015-2018 DoDs, whereby bars appear to be both migrating downstream and accreting laterally. This is the first field-based study to explicitly link the path length distribution with morphological development in the channel for a wandering gravel-bed river. It also provides some verification of the bi- and multi-modal path length distributions observed in flume experiments of bar-dominated channels (Pyrce and Ashmore 2003a).

In a smaller wandering channel - the Bouinenc Torrent, France (b = 24 m; Q_{max} = 41.1 m³/s) – Liébault et al. (2012) used PIT tags to track sediment over a two-year period. They found that a power law best modeled the distribution of tracer path lengths. In this study, Liébault et al. (2012) noted that tracer displacements were on the order of tens of metres when seeded on gravel bars, but were significantly
larger for tracer seeded closer to the thalweg. They describe a morphological regime in which the bars are simply storage units, and do not significantly contribute to bedload transport except during rare and extreme events which destroy or alter the bars (which was not observed during the tracer monitoring period in their study). Overall particle dispersion was high and bars did not act to trap bedload material.

Despite both rivers being classified as wandering channels, particle tracking results from the San Juan River are in direct contradistinction with the Bouinenc Torrent. In the San Juan River, DoDs showed significant vertical and lateral accretion of bars with corresponding erosion of the opposite banks. Particle path lengths showed distinct modes related to bar development, indicating that bar dynamics are fundamental in the bedload transport regime for the San Juan River. The differences between the path length distributions for these two rivers, despite both being classified as wandering channels, is inherently caused by the disparate hydrological and morphological conditions of the two rivers. In the large, dynamic channel of the San Juan River, particle transport is slaved to the bar dynamics since bars appear to be re-worked with some regularity. In this situation, particle transport is on the intrabedform scale, with bi- or multi-modal path length distributions related to bar development. In the smaller Bouinenc Torrent, the channel is steeper and has a more stable morphology, resulting in high particle dispersion whereby tracers were able to freely move along the low-flow channel without impedance from the bars. In this situation a power-law best described particle transport. This directly highlights the importance in considering both flow conditions and morphodynamics for modeling the transport of sediment in different systems.

There are two previously published papers that have used PIT tags to track bedload sediment movement in large, dynamic, bar-dominated rivers – Rollet et al. (2008) and Chapuis et al. (2015). While neither of these studies were deliberately focused on describing the shape of the path length distributions, observations from these studies lend credibility to the pattern of tracer transport observed in the San Juan River. In the Ain River, France (b = 75-100 m; Q_{max} = 800 m^3/s), Rollet et al. (2008) recovered 36 % of their tracers after one year, with an average travel distance of just 50 m, indicative of intrabedform transport. In the Ain River study, tracers were seeded at the head of a gravel bar – a similar deployment strategy as in the San Juan River. This section of channel was laterally dynamic, with repeat topographic surveys revealing that a thick sedimentary layer had accreted on the edge of the gravel bar immediately downstream of the tracer deployment location. They suggested that the low recovery rate in this experiment was in part caused by the potentially deep burial of tracers (beyond the antenna’s maximum range of detection) associated with the thick sedimentary layer that had manifested on the bar edge. This description is strikingly similar to the lateral accretion of bars observed on the San Juan River (especially
Bar 6) identified as sites of tracer clustering. On the Durance River, France ($b = 290 \text{ m}; Q_{\text{max}} = 1156 \text{ m}^3/\text{s}$), Chapuis et al. (2015) recovered 40% of their tracers after four months, with an average travel distance of 83 m, again indicative of intrabar transport. The deployment strategy used in this study was to place five transects of tracers across the mid to lower portion of a gravel bar. They reported that tracers deployed on bar tails tended to remain immobile or were only displaced short distances, while those seeded closer to the thalweg experienced higher transport distances, in agreement with results from the San Juan River. This highlights the spatial variability in bedload transport in these types of rivers, and suggests that deployment strategy has an influence on the observed transport distances and relative mobility of tracers in large wandering channels. In the cases of the Ain, Durance, and San Juan Rivers, tracers tend to remain within one morphological unit, with minimal transport downstream. This provides direct evidence that in addition to hydraulic controls, channel morphodynamics influence particle transport in these types of rivers, and particle trapping and burial in association with bar development appears to be an important consideration in modeling sediment behaviour.

6.1.1 Significance of Individual Particle Transport over Longer Time-Scales
The path length distributions presented in this thesis reflect particle transport over one to three years. However, there is reason to believe that these results reflect longer term patterns in bedload transport for the San Juan River. The peak flows from the three years of tracer movement are not uncommonly large or small when compared with the historic hydrologic record, so there is no reason to assume anomalous movement due to the magnitude of peak floods. Perhaps more importantly, the preferential deposition and incorporation of tracers in bars has been previously demonstrated to hold true over longer time-scales in gravel-bed rivers in general (e.g. Ferguson et al., 2002; Haschenburger, 2013). On the most fundamental level, bars are, by definition, depositional environments, formed by the accumulation of individual particles. When viewed through this lens, it is perhaps not surprising that short-term particle path lengths on the San Juan River have modes associated with changes in the bars, since the bars appear to be re-worked by annual peak floods. Additionally, since tracers tended to remain in one morphological unit, with limited transport downstream, the bars are evolving over time and we can expect that they will continue to trap particles as they grow in size. Therefore, the absolute magnitude of particle path lengths will likely decrease over time as tracers are preferentially deposited at and stored in bars, becoming less likely to be re-mobilized than particles on the bed surface and/or closer to the thalweg. However, the accumulation of tracers in these distinct regions related to bar development is likely to persist as long as the current hydromorphological conditions that maintain the contemporary channel morphology persist.
Descriptions of bar growth and evolution in a wandering reach of the Fraser River, BC, by Church and Rice (2009) and Rice et al. (2009), are consistent with the pattern of erosion and deposition of the San Juan River DoDs. Rice et al. (2009) showed that net annual changes in sediment storage for two gravel bars were comparable to the bedload transport rate for the channel calculated from long-term sediment budgeting. This indicated that relatively low amounts of bed material were bypassing the bars, and that bar construction and erosion were the fundamental processes involved in bedload transport for the channel. This description of bedload transport seems consistent with the intra-bar transport observed in the San Juan River, as only few tracers were transported past the initial bar downstream of their initial position. Church and Rice (2009) described the three-dimensional growth of gravel bars in the Fraser River over the century scale, noting that they quickly reach a vertical equilibrium, after which sediment is no longer lifted onto the bar top. After this stage, bars grow primarily via lateral accretion, leading to a laterally unstable channel, with vertical accretion on the bar tail. A similar pattern of deposition was observed for bars in the San Juan River, which exhibited both lateral accretion and vertical accretion on the downstream portion of the bar surface. Rice et al. (2009) also noted that the lateral accretion of bars may persist over long time-scales, as one bar in the Fraser River exhibited rapid lateral accretion over a 65 year period, which consistently forced the main channel to migrate away from the bar, leading to a linked pattern of bar accretion, bank erosion, and subsequent deposition of the bank material on downstream bars. The long-term processes acting upon this reach of the Fraser River appear to be similar with observed morphological changes in the San Juan River. This suggests that the intrabedform transport of tracers, particularly along the bar-pool margin, may persist over longer time-scales than the annual scale reported in this thesis, and is related to the style of bar development (e.g. gradual downstream migration of bars and bends).

In the San Juan River, the active alluvial channel has widened between 1995 and 2018 (Figure 3.10), and measurements from NHC Ltd. (1994) indicate that channel widening dates back as far as 1955. This long-term pattern of lateral instability appears to be associated with lateral and vertical accretion on bars accompanied by bank erosion opposite the bars. Since the deposition and burial of tracers aligned well with areas of deposition in the DoDs, this provides evidence that individual particle displacements are the building blocks for short-term bar development, which in turn controls the overall channel morphodynamics over the decade scale.

The observed pattern of bar expansion and bank erosion, typical of wandering channels, likely has direct impacts on available physical habitat for fish in the San Juan River. Bar migration (and riffle expansion)
minimizes pool area, a crucial environment that juvenile salmonids use to hide from stronger flows (MacIsaac, 2010). The subsequent bank erosion then alters the composition of sediment in the channel, since the banks are composed of much finer material than typically found on the bed surface (Hogan and Luzi, 2010). This also impacts fish habitat, since Pacific salmonid species require coarse, permeable substrates for spawning (MacIsaac, 2010). Based on the morphological changes observed in the 2015-2018 DoDs, bar expansion and bank erosion remain the dominant fluvial processes in the mainstem, which suggests that the increased sediment supply in the latter half of the twentieth century (NHC Ltd., 1994) may still be working through and stored in the lower alluvial reach of the river. As such physical habitat in the channel will continue to be impacted.

One facet of the San Juan River bedload transport regime that was neglected in this study was the potential routing of particles along chute channels present on the inside of many of the bars. Tracer launch lines were established across riffles between the head and tail of alternate bars resulting exclusively in tracer transport along the mainstem. However, if the launch lines had been moved upstream of bar heads, some fraction of the tracer population may have been re-routed along the inside of bars through chute channels. A relative elevation model of the San Juan River between Bars 6 and 7 is presented in Figure 6.1 to illustrate the presence and location of chute channels on Bar 6. The DoD of Bar 6 (Figure 5.23) displays deposition along one of the chute channels. The sediment calibre is predominantly fine gravel and sand, though coarse gravel is also present (Figure 6.2) indicating that bedload is transported through this area. These channels provide a route for sediment to be transported to the bar tail bypassing the main channel around the bar. Previous studies have demonstrated that development of chute channels in wandering reaches can lead to lateral (or point) bars becoming ‘cutoff’ from the banks, which can trigger significant morphological adjustments downstream (Fuller et al., 2003a). However, the relative importance of these channels in transporting bedload sediment in the San Juan River is unclear based on this study, though their existence indicates that they play a role in sediment transport regime. Further research is required to investigate this component of bedload transport in wandering channels and their impact on particle path length patterns.
Figure 6.1. REM of the Bars 6-7 reach of the San Juan River. Red lines depict tracer launch line positions. The blue arrow shows flow direction.

Figure 6.2. Sediment calibre in the chute channel near the head of Bar 6.
6.1.2 Comparison of Particle Transport between the San Juan River and its Tributaries

Individual particle transport on the San Juan River tended to focus along the bar-pool margin, with clusters of tracers deposited at or downstream of the bar apex, and few tracers transported past the initial gravel bar downstream of their seeding location. The Harris Creek path length distribution showed similar peaks in tracer accumulation associated with the initial bar apex and downstream riffles. However, Harris Creek also had frontrunner tracers that travelled more than a kilometre downstream over two years, ending up in the mainstem. It appears that whilst sediment accumulating on bars and riffles does influence the path length distribution for Harris Creek, interbedform transport was more common than on the mainstem, and sediment is flushed through this channel at a faster rate. The path length distribution for Lens Creek is hard to interpret and does not show any recognizable association to morphologic features in the channel. Generally, tracers displayed lower mobility and shorter path lengths than in Harris Creek, which may suggest that Lens Creek is a less significant sedimentary source to the lower San Juan River. Though this finding requires more thorough testing, it provides some basic insights into the relative importance of the tributaries to the mainstem sediment supply, which was one of the main goals of the larger geomorphological assessment of the watershed.

6.2 Hydraulic Forcing and Grain Size Effects on Particle Transport

In this section average particle transport distances from this study are compared with previously defined relations with metrics for flow strength and grain size. The flow strength relations are only compared with data from the San Juan River, since no direct measure of discharge was recorded for Harris or Lens Creeks.

6.2.1 Hydraulic Forcing

In the literature, tracer studies have used several metrics to characterize the magnitude of flow strength, such as peak stream power, excess peak stream power, and excess velocity (Hassan and Bradley, 2017). One metric, developed by Eaton and Church (2011), provides a dimensionless form of unit stream power:

$$\omega^* = \frac{\omega}{\rho \ (g \ R \ D)^{\frac{3}{2}}}$$

(6.1)

Where $\omega^*$ is dimensionless unit stream power, $\omega$ is peak unit stream power, $\rho$ is the density of water, $g$ is the acceleration due to gravity, $R$ is the submerged specific weight of sediment, and $D$ is a representative grain size for the bed surface, typically the median bed surface size (Vázquez-Tarrío et al, 2018). Peak unit stream power was calculated as:

$$\omega = \frac{\rho \ g \ S \ Q_{max}}{b}$$

(6.2)
Where S is the reach-averaged channel slope, Q_{max} is the peak discharge, and b is the reach-averaged channel width. Vázquez-Tarrío et al. (2018) used this version of stream power to compare the influence of hydraulic forcing on mean tracer travel distances across a range of tracer case studies of different scales. To compare the transport of tracers from different studies, they also scaled particle travel distances by a ‘morphological length scale’ of the respective channels (i.e. the distance between macroscale bedforms). This was an attempt to account for the dependence of particle movement on the channel morphology. To compare the San Juan River tracer transport with these results, the dimensionless unit stream power and mean scaled travel distance for Bars 6, 7 and 15 were calculated for each year of deployed tracers. Bar 6 tracers from 2015 were not included due to the low recovery rate and assumed underestimate of travel distances. The annual peak discharge recorded at the hydrometric station was converted to an estimated discharge at each tracer deployment site by scaling via watershed area (Coulson and Obedkoff, 1998). A major limitation of using dimensionless peak discharge as a metric for analysing the effects of hydraulic forcing for the San Juan River, is that multiple events likely mobilized tracers and are not accounted for by this metric. Additionally, using mean travel distances may not be a good reflection of the average movement of particles, since tracer path length distributions are not normally distributed and frontrunners skew mean travel distances. However, these variables were used to analyse previous passive tracer data, and so for comparison with past studies the same metrics were used for the San Juan River dataset. Results are presented in Figure 6.3, an adapted version of Figure 4 from Vázquez-Tarrío et al. (2018).
The data from the San Juan River plot closely to the line of best fit for riffle pool and multi-thread channels calculated by Vázquez-Tarrío et al. (2018), showing a positive relationship between the mean scaled travel distance and dimensionless unit stream power. What is more interesting perhaps, and was noted by Vázquez-Tarrío et al. (2018), is that riffle-pool channels share a commonality in that they rarely exhibit average travel distances beyond 1-2 length-scale units, indicating that particle dispersion is low in this channel type relative to other morphologies. The upper limit for mean particle transport in riffle-pool channels appear to be around 2-2.5 morphological length scale units. This is substantially lower than mean travel distances for other channel morphologies. Step-pool channels exhibited mean travel distances in excess of 50 morphological length-scale units, while plane-bed channels had mean travel distances consistently between 2-5 morphological length-scale units, but as high as 20. This indicates that downstream transport of tracers in riffle-pool channels is limited compared with other channel types, and that macroscale bedforms (presumably bars and riffles) are trapping and constraining particle movement in riffle-pool channels. So the longer term transport rate is slaved to the rate of bar development and migration. Overall, the San Juan River data appears to show relatively low travel distances for a given stream power which is likely an artefact of using the dimensionless peak discharge to capture hydraulic

**Figure 6.3.** Mean scaled travel distance of tracers as a function of dimensionless unit stream power, adapted from Vázquez-Tarrío et al., 2018. RP = riffle-pool, MT = multi-thread, SP = step-pool, and PB = plane-bed. Unconstrained refers to tracer experiments in which particles are deployed on the bed surface, and constrained refers to results for tracers incorporated into the subsurface.
forcing, as opposed to capturing the total discharge above the critical value for gravel entrainment across all mobilizing events. It also may point to the fact that bars in the San Juan River are particularly successful at restricting tracer transport.

6.2.2 Grain Size
As previously mentioned, past research has shown that the grain size of tracers relative to the size of local subsurface bed material shows a stronger correlation with mean travel distance than does the absolute size of the particle (Church and Hassan 1992; Hassan and Church, 1992; Wilcock, 1997). Hassan and Bradley (2017) summarized results from previous tracer studies showing the relationship between the scaled travel distance of particles as a function of the scaled particle size. Where mean travel distances of each tracer size class were scaled by the travel distance of the class which included the local surface $D_{50}$, and the tracer size class was scaled by the local subsurface $D_{50}$. Results from the San Juan River, Harris and Lens Creek were plotted on an adapted version of this graph in Figure 6.4. Note that the local subsurface $D_{50}$ was not measured in this study, so tracer class sizes were scaled by the local surface $D_{50}$. The midpoint of each tracer size class was used to define the diameter of tracers within the class (e.g. 22-32 mm tracers were considered to have a diameter of 27 mm).
While the results from this study show a general negative relationship between scaled mean travel distance and scaled particle size, the data tend to plot outside of the 95 % confidence interval defined by Church and Hassan (1992). One explanation for this may be that scaling grain size by the surface $D_{50}$ as opposed to the subsurface $D_{50}$ produced the differences from previous studies, as the channels in this study appear to be armoured (based on field observations). However, the compiled data already show a large amount of scatter in the grain size-travel distance relationship, so while coarser grains are generally transported shorter distances downstream, it appears that the size-dependent transport of individual

Figure 6.4. Scaled travel distance of tracers as a function of scaled particle size, adapted from Hassan and Bradley, 2017. The particle size for results from this study were scaled by the surface $D_{50}$ since the subsurface $D_{50}$ was not known.
particles does not follow a strict relationship universal across all channels. For example, on smaller streams with plane-bed channels simple physical explanations such as the inertia of coarser particles, and the trapping of smaller particles in the interstices between coarse particles have been posited as explanations for the grain size-travel distance relation (Church and Hassan, 1992). Wilcock (1997) demonstrated that for flow conditions close to the threshold for gravel entrainment, that the finer fraction of the bed may become fully mobilized, whilst the coarse fraction is selectively transported based on grain size. However, for a dynamic river such as the San Juan River, tracers exhibited high relative mobility, with around 80% of particles mobilized for most deployments. This suggests that other processes may be affecting the grain size-travel distance relation compared with smaller, less complex streams.

Pyrce and Ashmore (2005) suggested that size-sorting effects around bars may influence particle transport for riffle-pool channels, as coarser particles typically cluster on bar heads and riffles, whilst finer particles tend to be deposited on bar tails. A cursory analysis of size-dependent median path lengths was explored for this dataset. Typically, coarser tracers clustered in the initial riffle in which they were seeded, whilst downstream clusters, associated with bar apexes and riffles, were comprised of intermediate sized ($\sim D_{50}$) and finer tracers. For tracers seeded on Bar 6, the migrating gravel sheet at the bar apex appeared to trap sediment of all sizes, though a small fraction of finer particles were transported to the bar tail. These general observations shed some preliminary insight into the possibility of size-dependent path lengths developing in association with bar sedimentation and morphology. So in Figure 6.4 while the data trends may be similar, the causes might be different. This would mean that for predictions of size-dependent sorting, different models are needed to account for the processes driving these trends in bar-dominated channels. In these systems, particle transport appears much more dependent on initial location, as particles seeded on bar tails are typically relatively immobile or transported only short distances, due to the lower shear stress experienced in these depositional environments (Liébault et al., 2012; Chapuis et al., 2015). Therefore, the whole dynamics of particle transport and dispersion is different from smaller streams lacking well-developed bar morphologies. Comparison of grain size-travel distance plots across different channel types may reveal general patterns, but the controls on these may be different. A more thorough statistical analysis is required to investigate size-sorting effects in bar-dominated channels. Characterization of the spatial variations in the size of bed material across the bar/channel would help provide context to size-dependent tracer clustering.
6.3 Tracer Recovery Rates
Bedload sediment was tracked using PIT tagged tracers in the lower San Juan River, Harris Creek and Lens Creek. Recovery rates for individual sites ranged from 63 to 81 %, with an overall recovery rate of 72 % across the entire dataset (Table 5.1). Chapuis et al. (2015) provided a synthesis of RFID tracer studies tracking bedload in rivers prior to 2014. An adapted version of this synthesis is presented Table 6.1, updated with more recently published tracer studies including results from this study. The recovery rate achieved for the San Juan River (73 %) is higher than previous RFID bedload tracking studies conducted at similar spatial and temporal scales (Table 6.1).
Table 6.1. Synthesis of bedload transport studies using RFID tracer stones in rivers, adapted from Chapuis et al. (2015).

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Study Area(s)</th>
<th>b (m)</th>
<th>$Q_{\text{max}}$ (m$^3$/s)</th>
<th>N</th>
<th>T (months)</th>
<th>n</th>
<th>R (%)</th>
<th>$d_{\text{max}}$ (m)</th>
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<td>Nichols</td>
<td>2004</td>
<td>Walnut Gulch, Arizona</td>
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<td></td>
<td>124</td>
<td>2</td>
<td>4</td>
<td>94-98</td>
<td></td>
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<td>2005</td>
<td>Moras Creek, Quebec</td>
<td>7</td>
<td>3.5</td>
<td>204</td>
<td>8</td>
<td>2</td>
<td>87-96</td>
<td></td>
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<td>CARRÉ et al.</td>
<td>2007</td>
<td>Nicolet River, Quebec</td>
<td>35</td>
<td>21.1</td>
<td>110</td>
<td>3</td>
<td>3</td>
<td>97</td>
<td>97.3</td>
</tr>
<tr>
<td>Rollet et al.</td>
<td>2007</td>
<td>Ain River (Varambon), France</td>
<td>75</td>
<td>800</td>
<td>150</td>
<td>12</td>
<td>1</td>
<td>25</td>
<td>96</td>
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<tr>
<td>Rollet et al.</td>
<td>2007</td>
<td>Ain River (Gevreux), France</td>
<td>100</td>
<td>800</td>
<td>400</td>
<td>12</td>
<td>1</td>
<td>36</td>
<td>96</td>
</tr>
<tr>
<td>Lamarre and Roy</td>
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<td>204</td>
<td>18</td>
<td>5</td>
<td>84-100</td>
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<td>42</td>
<td>2</td>
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<td></td>
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<tr>
<td>Rollet et al.</td>
<td>2008</td>
<td>Moras Creek, Quebec</td>
<td>6</td>
<td>214</td>
<td>27</td>
<td>4</td>
<td>87-90</td>
<td>&gt; 500</td>
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<tr>
<td>Camenen et al.</td>
<td>2010</td>
<td>Arc River, France</td>
<td>70</td>
<td>500</td>
<td>300</td>
<td>10</td>
<td>3</td>
<td>12-80</td>
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<td>Schneider et al.</td>
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<td>8</td>
<td>30</td>
<td>&gt; 350</td>
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<td>~ 20</td>
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<td>5</td>
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<td>5</td>
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<td>35</td>
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<td>54-100</td>
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<td>Bradley and Tucker</td>
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<td>Bounenc Torrent, France</td>
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<td>41.1</td>
<td>451</td>
<td>26</td>
<td>25-78</td>
<td>2229</td>
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<tr>
<td>Gaeuman</td>
<td>2013</td>
<td>Grass Valley Creek, California</td>
<td>6-9</td>
<td>~ 12.7</td>
<td>482</td>
<td>60</td>
<td>49-69</td>
<td>60.4</td>
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<tr>
<td>Milan</td>
<td>2013</td>
<td>River Rede, UK</td>
<td>9-18</td>
<td>11.9</td>
<td>98</td>
<td>18</td>
<td>43-92</td>
<td>93.2</td>
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<tr>
<td>Phillips and Jerolmack</td>
<td>2014</td>
<td>Mamayes River, Puerto Rico</td>
<td>20</td>
<td>300</td>
<td>36</td>
<td>9</td>
<td>62-100</td>
<td>1200</td>
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<tr>
<td>Chapuis et al.</td>
<td>2015</td>
<td>Durance River, France</td>
<td>290</td>
<td>1156</td>
<td>232</td>
<td>4</td>
<td>1</td>
<td>40</td>
<td>668</td>
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<td>Dell’Agnese et al.</td>
<td>2015</td>
<td>Lower Strimm Creek, Italy</td>
<td>4</td>
<td>1.81</td>
<td>231</td>
<td>33</td>
<td>54.7-100</td>
<td>959.3</td>
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<td>1.13</td>
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<td>17.1-48</td>
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<td>~ 67</td>
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<td>2480</td>
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<td>60</td>
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<td>Rainato et al.</td>
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<td>McQueen (this study)</td>
<td>2019</td>
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<td>1022</td>
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<td>3</td>
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<td>218</td>
<td>22</td>
<td>2</td>
<td>73</td>
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</table>

**NOTE:** $b$ – active width; $Q_{\text{max}}$ – maximum discharge; N – number of tracers deployed; T – length of time of the study; n – number of tracking surveys; R – recovery rate; $d_{\text{max}}$ – maximum transport distance.
6.3.1 Limitations on Recovery Rates and Recommendations for Future Field Campaigns

The distribution of particle deposition and burial, in combination with the spatial patterns of erosion and deposition from DoDs, reveals insight into possible factors hindering tracer recovery rates for the San Juan River. On the mainstem, deep tracer burial occurred at two main regions: 1) for tracers seeded on the tail of bars; and 2) for tracers transported to and incorporated in the bedload sheet at the apex of Bar 6. In both of these situations, it seems plausible that unrecovered tracers may reside in these areas but were not detected either due to burial beyond the antenna’s maximum range of detection, or more likely, due to the clustering of PIT tags in one area causing signal interference (Lamarre et al., 2005; Chapuis et al., 2014; Arnaud et al., 2015). High rates of bar sedimentation and downstream bar migration have been documented in other wandering gravel-bed channels (Fuller et al., 2003a; Rice et al., 2009), which suggests that future tracing experiments on similar rivers should take these factors into consideration. Tracer clustering on bar tails may be avoided by implementing a deployment strategy that focuses on more active erosional parts of the channel and not seeding tracers on bar tails at all. Detecting PIT tags in areas of tracer clustering associated with downstream sedimentation is trickier to solve. One possible solution could be to scan the bar-pool margin from multiple directions, which would increase the likelihood of detecting PIT tags due to their anisotropic detection zone. Recently Papangelakis et al. (in press) designed synthetic tracer stones that are weighted by an inner ball, which ensures that the PIT tag remains vertically oriented, resulting in optimal conditions for antennas to detect the tag. This could prove to be a useful tool for particle tracking in dynamic channels where thick sedimentary units have the potential to deeply bury tracers.

A second source of error limiting tracer recovery was the presence of pools too deep to survey by foot. It is likely that some portion of unrecovered tracers were deposited in these areas, though pools are erosional features and not likely to be the focus of high bedload deposition. In a recent study by Arnaud et al. (2017) deep-water areas of the Old Rhine were searched by boat. A large antenna was towed along the riverbed and tracer positions were recorded by an on-board differential GPS with horizontal tracer positions estimated within ± 5 m. The combination of pedestrian and boat surveys could improve tracer recovery rates on the San Juan River, and more generally in large rivers with deep pools, though the process would be time- and personnel-intensive (Arnaud et al., 2017).

The use of a portable antenna capable of detecting 32 mm PIT tags up to 1.75 m away in ideal conditions was crucial in achieving a high recovery rate for the San Juan River. During the initial year of tracer
surveying, only the smaller wand antenna was used, which resulted in just 33 of 100 tracers being recovered in the summer of 2016. The following two years of surveys implemented a combination of the small antenna with the large antenna, and considerably higher recovery rates were achieved. Also, a further 43 and 5 tracers were recovered in the summers of 2017 and 2018 respectively from the initial set of 100 tracers, totalling 81 of 100 tracers recovered over the three surveys. A high fraction of these tracers were recovered in areas that had previously been searched during 2016, leading to the conclusion that either they had been re-exposed by scour during floods in the winter of 2016, or, more likely, that they were buried at depths exceeding the small antenna’s maximum detection range. The combination of antennas was also an effective method of searching for tracers, as the large antenna often had difficulty detecting immobile tracers along the launch line, whereas the signal interference was less of a problem for the small antenna.

The spatially variable nature of bedload transport in wandering channels emphasizes the importance in choosing an appropriate tracer deployment strategy. For example, if tracers are seeded on bar tails they are unlikely to be mobilized. Depending on the objective of the study, future particle tracking experiment should consider seeding tracers upstream of bar heads to account for the possible routing of particles along the inside of bars via chute channels. Additionally, in searching for tracer stones in dynamic, bar-dominated rivers, surveys should allot more time and attention to thoroughly searching the bar-pool margin and riffles, as opposed to extending the search area longitudinally. The second bar downstream exhibited a much sparser distribution of tracers than the first bar downstream of tracer seeding locations, indicating that tracers tended to remain in the initial riffle-pool-bar sequence. This finding has been reported in other particle tracking experiments of wandering channels (Rollet et al., 2008; Chapuis et al., 2015). Ultimately, future studies need to consider deployment strategies in terms of morphology and the process(es) they are trying to document.

6.4 Topographic Surveying
A major limitation of this study, was the lack of topographic data captured in-channel. The LiDAR sensor was only capable of penetrating shallow riffles, and no data was captured in the pools. If bathymetric data could be acquired then a complete DEM of the active channel could be produced. This is particularly desirable, because it would allow for a more complete budget of sediment storage in the channel. Furthermore, if an estimate of the total volume of erosion from a reach could be established, this can be combined with tracer path lengths to infer the bedload transport rate for the reach (Vericat et al., 2017). Bathymetric data would also allow a more detailed and accurate estimate of the magnitude of lateral
accretion on bar edges, which appears to be one of the most significant morphological processes acting in wandering channels.

In this study, the spatial distribution of tracers could only be linked with net changes in the channel over a two and a half year period between LiDAR surveys (October 2015 – February 2018). Annual, or even event-based, surveys would help directly link specific depositional and erosional processes with individual particle displacements. Additionally, estimating the magnitude of change associated with different fluvial processes was inherently tricky since scour from one event can be compensated by fill from subsequent events, and vice versa, so only net changes could be observed (Lindsay and Ashmore, 2001). Unmanned aerial vehicle (UAV) surveys were conducted between 2016 and 2018 for this study with the intent of increasing survey frequency, but output DEMs were unreliable for topographic change due to the lack of reliable ground control and uncertainty in the associated errors. As such UAV-collected data were not included in this thesis. With more consideration paid to georeferencing UAV data, high-resolution DEMs and grain size maps would be especially useful data to contextualize particle movement and changes in channel morphology.

6.5 Tracer Burial and the Active Layer Depth
The depth of the San Juan River active layer was spatially non-uniform. Deposition appears to be maximized on bar edges and surfaces from the mid-bar downstream to the bar tail. Elevation changes from DoDs were as large as two metres of deposition, and three metres of erosion, with the maximum volume of change associated with 0.2 – 0.7 m of vertical accretion. Tracers also displayed a range of burial depths, including roughly 25-30 % of the tracer population buried deeper than 0.5 m on Bars 6 and 7. These burial depths are in exceedance of the commonly cited value of 2 D₉₀ (roughly 0.2 m for the San Juan River) as the maximum active layer depth in gravel-bed rivers (Hassan and Bradley, 2017). This indicates that the concept of a shallow active layer of uniform depth is not an appropriate model for the San Juan River. Maximum tracer burial depths appear to be comparable to the elevation changes responsible for the largest volumetric changes in DoDs. In an ideal situation, if DoDs were available prior to particle tracking, then the elevation change causing the maximum volumetric changes can be used to give a rough idea of maximum tracer burial depths, and thus the experiment and equipment can be designed accordingly. For rivers of a similar size and style to the San Juan River, future studies require antennas with a maximum detection range of at least 0.5 m, and potentially as high as two metres, to mitigate the loss of tracers due to deep burial.
6.6 Implications for Restoration Work and Future Studies

The underlying goal of restoration work in the San Juan River Watershed is to improve and increase physical habitat for salmonid species in the river. This requires gathering background information on the bedload transport regime in the mainstem and tributaries, monitoring morphological changes, and assessing the impacts of increased sediment delivery to the lower alluvial reach during the latter part of the twentieth century (NHC Ltd., 1994). The results of this thesis provide some insights into these problems, in particular the bedload transport and morphodynamics of the San Juan River, which should also be transferable to similar rivers.

One of the main initiatives undertaken as part of the restoration work was the planting of willows on gravel bars. This was intended to stabilise bars, and force the river to scour a narrower and deeper mainstem channel (Polster, 1999). The results of change detection from 2015 to 2018 show that the mainstem bars monitored in this study are expanding. Vertical accretion is occurring on the bar surface from the mid-bar to the bar tail, and bars are growing laterally, with maximum deposition focused at the bar apex region. Bars 6 and 7 are more morphologically active than Bar 15. This pattern of deposition results in bend and bar migration, with erosion of the opposite banks, causing lateral instability and overall channel widening. It is unclear at this point to what extent willow planting is contributing to deposition on bars, since bar growth has been observed over the past several decades. Future studies are needed to monitor topographic changes on willow-planted bars in comparison to non-planted bars in order to evaluate the effects of this work.

The high sediment supply to the lower alluvial reach of the San Juan River, as reported by NHC Ltd. (1994), appears to still be working through the system, and may continue for years. Particle dispersion is relatively low in the San Juan River, with grains tending to remain with a single riffle-pool-bar sequence. Particles are preferentially deposited and buried along bar margins, becoming incorporated into the bars. This is causing the bar growth observed in this study, and documented over the longer-term (NHC Ltd., 1994). The bank erosion occurring in response to lateral bar development is inputting fine sediment to the channel, affecting bed substrate composition downstream, which is of concern for the spawning habitats of salmonid species (MacIsaac, 2010). Presumably, the sediment eroded from banks is transported to the first depositional site downstream, though that was not directly addressed in this study. It would be worthwhile to investigate the fate of this sediment, which would require different tracking techniques, capable of monitoring sand and silt-sized material.
To fully address the question of whether or not the logging-related supply of sediment to the lower San Juan River has been flushed through or is still working through the system, a more complete sediment budget is required across the entire active channel. Integration of bathymetric data with surveys of the exposed channel are necessary for this. Recently, a high-resolution digital terrain model of a channel of similar dimensions to the San Juan River was generated by Flener et al. (2013), using UAV photogrammetry, terrestrial LiDAR scanning (TLS) and in-channel profiling using an Acoustic Doppler Channel Profiler (ADCP). Using these methods, a more complete reach-scale morphological sediment budget could be determined, which would reveal whether the river is in equilibrium or if it is net depositional, due to a sediment supply higher than the rate at which the river is able to convey sediment. This would also allow the rate of lateral accretion along bar margins to be better quantified, which is particularly relevant since this appears to be one of the most important fluvial processes in rivers of this type.

Future studies on the San Juan River, or other rivers of similar scale and morphologic style, should account for the contribution of chute channels to the bedload transport regime. Lateral bars dominate in the mainstem of the San Juan River as opposed to medial (or mid-channel) bars, which suggests that chute channels are not actively cutting off bars from the banks. Over the long term however, chute channel cutoff should be considered in monitoring channel morphodynamics and particle transport in wandering channels, as this has been reported as an important process in other rivers of this type (Fuller et al., 2003a; Rice et al., 2009).

Sediment dispersion in Harris Creek appears to be relatively high, as the farthest moving tracers were recovered in the mainstem after two years having been transported more than 1.5 km. Also, there were high burial rates and depths for tracers at the Harris Creek launch line, indicative of sediment supply from upstream. Overall, it appears that Harris Creek remains a significant sediment source to the mainstem. Lens Creek, however, showed low particle mobility and median path lengths, with little observed morphological changes. These results are tentative at best since change detection in Lens Creek was limited due to survey quality, and particle tracking was only conducted for the first 500 m of channel downstream yet particle dispersion may have exceeded this extent. There are fewer bars in general in Lens Creek relative to Harris Creek, indicating that there are less sediment storage sites. Based on these insights, Lens Creek appears to be a less significant sediment source to the mainstem than Harris Creek.
Chapter 7: Conclusion

The primary goal of this thesis was to investigate the interplay between channel morphology and individual particle dynamics for a wandering channel. This was achieved by coupling individual particle tracking using PIT tagged tracer stones and measuring morphologic changes through repeat airborne LiDAR surveys. This study is one of very few particle tracking experiments conducted on a large, wandering channel, and as such provides important information on the nature of bedload transport in these systems.

Tracers exhibited bi- and multi-modal path length distributions, with modes related to bar apexes and riffles, but also to areas of deposition from DoDs. These path length distribution shapes, exhibiting morphologic ‘signals’, have been previously observed in flume experiments, but this is one of the first studies to demonstrate this pattern of particle transport and deposition in the field. Tracer transport was focused along the bar-pool margin, indicative of lateral bar growth, and few tracers were transferred downstream of the initial riffle-pool-bar sequence in which they were seeded, highlighting the trapping effect of bars. These findings lend credence to the notion that, in addition to hydraulic forcing, the details of particle transport are affected by channel morphology and bar dynamics in morphologically active rivers.

In addition to linking short term particle displacements and morphologic changes in the channel, these processes were compared with longer term changes in the river. Channel widening has been documented in the San Juan River as far back as 1955. This appears to be driven by a sequence of bar expansion and development, followed by erosion of the opposite bank, leading to a laterally unstable channel, giving the river its wandering habit. This suggests individual particle dynamics are ultimately interlinked with the morphological style of the channel.

This study achieved the highest rate of tracer recovery for a river of this scale with 73 % of tracers recovered on the mainstem. The implementation of a large, portable antenna provided an effective method of searching large surface areas of channel, while the smaller antenna helped mitigate signal interference for locations where PIT tags were in close proximity. Tracer burial depths were found in excess of 0.5 m, with deposition focused on the bar tails and margins. Future tracing experiments should avoid seeding tracers on bar tails, and emphasize the time spent surveying bar margins. Overall, this study provides promising results for the viability of PIT tags as a particle tracking technique in dynamic gravel-bed channels.
References


Appendix A – LiDAR Specifications

2015 Survey

Geodetic Parameters

- Horizontal Datum: NAD83 (CSRS)
- Vertical Datum: CGVD28
- Geoid: HTv2.0
- Projection: UTM Zone 10 N
- Units: Metres

LiDAR Point Density

- $\geq 12$ pulses / m$^2$

Orthophoto Resolution

- 5 cm pixel resolution

Acquisition Details

- Collection platform: Bell 206B
- Flying Height (AGL): 1200 m
- Acquisition Speed: 100 km/h
- Lateral Flight Line Overlap: 100 %

System Parameters

- Laser Type: Riegl LMS-Q780
- Camera Type: Nikon D800E

Accuracy Reporting

- Vertical Accuracy Report – Static:

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<th>Control Point</th>
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<tr>
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- Number: 2
- Average dZ: $-0.005$
- Minimum dZ: $-0.031$
- Maximum dZ: 0.000
- Average Magnitude: 0.026
LiDAR Collection Statistics

- 37% of project area had greater than 12 points per square meter density based on first return point cloud
- Total project area: 82.84 km²
- LiDAR Acquisition Dates: October 23 and 24, 2015
- Average density: 12.8 points/m²
- Standard deviation: 7.2 points/m²
- Cell size: 20 m

2018 Survey

Geodetic Parameters

- Horizontal Datum: NAD83 (CSRS)
  - Epoch: 1997.0
- Vertical Datum: CGVD28
- Geoid: HTv2.0
- Projection: UTM Zone 10 N
- Units: Metres

Planned LiDAR Point Density

- 9 points per square metre

Orthophoto Resolution

- 10 cm pixel resolution

Acquisition Details

- Collection platform: Bell 206B Jet Ranger
- Flying Height (AGL): 1000 m
- Acquisition Speed: 90 km/h
- Lateral Flight Line Overlap: 100%

System Parameters

- LiDAR:
  - Laser Type: Riegl LMS-Q780
  - Average Pulse Density: ≥ 9 points / m² (single pass, open hard surfaces)
  - Average Point Spacing (Uniform): 0.350 m
  - Laser PRF: 400 kHz
  - Mirror Scan Rate: 76 Hz
  - Max Scan Angle: ± 30 degrees
• Digital Imagery:
  o Camera Type: Nikon D800E
  o CCD Array: X = 7360, Y = 4912
  o Lens: 50 mm
  o Field of View: 39.5 degrees
  o Ground Sampling Distance: 10 cm

Accuracy Reporting

• Vertical Accuracy Report – Static:

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  o Number: 3
  o Average dZ: 0.011
  o Minimum dZ: -0.031
  o Maximum dZ: 0.037
  o Average Magnitude: 0.032
  o Root Mean Square: 0.032
  o Std Deviation: 0.037

• Horizontal Accuracy Report:

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<tr>
<td>---------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>WOOD</td>
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</table>

LiDAR Collection Statistics

• 75 % of project area had greater than 18 points per square meter density based on first return point cloud
• Total project area: 71 km²
• LiDAR Acquisition Dates: February 10, 2018
• Average density: 28 points/m²
• Standard deviation: 16 points/m²
• Cell size: 20 m
Curriculum Vitae

Name: Ryan McQueen

Post-secondary Education and Degrees:

University of Victoria
Victoria, British Columbia, Canada
2010-2016 B.Sc. (with distinction)

University of Western Ontario
London, Ontario, Canada
2017-2019 M.Sc.

Honours and Awards:

Natural Sciences and Engineering Research Council (NSERC)
Undergraduate Research Scholarship Award
2013

Related Work Experience:

Research Assistant
BC Ministry of Forests, Lands, Natural Resources, and Rural Development
2015-2018

Teaching Assistant
University of Western Ontario
2017-2019

Publications:
