

Flocculation and ingress of cohesive solids in a mountainous gravel-bed river

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

This thesis consists of an introductory chapter (Chapter 1), followed by five manuscripts chapters, written for publication in peer-reviewed scientific journals (Chapters 2 to 6), and a concluding chapter (Chapter 7). Rafaela de Freitas Maltauro is the sole author of Chapters 1 and 7, which were written under the supervision of Dr. Mike Stone and Dr. Adrian L. Collins. Chapters 2, 3, 4, and 5 have been published as open access peer-reviewed scientific journal papers, while Chapter 6 is currently under review. Chapter 7 is a synthesis of the research and discussion of the broader significance of the work. Exceptions to sole authorship of material and CRediT (Contribution Roles Taxonomy) are as follows:

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Abstract

Gravel-bed rivers draining mountainous headwater regions are critically important for the provision of high-quality drinking water and integrity in forested landscapes. These regions, however, have been increasingly impacted by natural (especially climate change-exacerbated) and anthropogenic landscape disturbances that can increase landscape connectivity and sediment delivery from hillslopes to receiving streams. Cohesive particles ($<63\ \mu\text{m}$) increasingly mobilized during landscape disturbances are key vectors for nutrient and contaminant transport across the catchment continuum. Excess delivery of fine sediment mobilized from landscape disturbances can cause deleterious physical, chemical and biological impacts on streams by increasing turbidity, compromising habitats, ecological integrity, and challenging water treatability. However, processes controlling the propagation and storage of cohesive solids in gravel-bed rivers are still poorly understood. Given the complexity of flocculation and ingress processes under turbulent flow fields and the lack of reported rigorous field observations, most hydrodynamic fine sediment transport models disregard these processes, potentially leading to inaccurate model estimations. Accordingly, the main goal of this thesis was to evaluate the processes of flocculation and ingress, and the effects of these processes on the propagation and storage of cohesive solids in a gravel-bed river through the integration of laboratory, field, and modelling approaches.

Five chapters were developed to achieve this goal: Chapter 2 investigated the *in-situ* characteristics of suspended sediment by measuring effective particle size distributions (LISST 200x) at four different sites of the study river at a range of flow conditions; Chapter 3 evaluated methods to measure fine sediment ingress rates and directional mechanisms by deploying >250 sediment traps, consisting of triplicates of three designs of sediment traps; Chapter 4, using those sediment traps, evaluated the hydraulic (discharge, water depth, Froude number, bed shear stress,

and stream power) and sedimentological (suspended sediment concentration by mass and by volume) drivers of fine sediment ingress; Chapter 5, using a rotating annular flume, characterized the processes of suspended sediment transport over different bed configurations through deposition, ingress, and erosion experiments, and; Chapter 6 calibrated and validated a semi-empirical cohesive sediment transport model (RIVFLOC) using results from the rotating annular flume, and applied the model to the observed field conditions to better understand the transport and fate of these particles in the study river.

Particles <500 μm in the Crowsnest River were predominantly transported in flocculated form. While the highest observed flow energy limited the development of larger flocs due to the breakage of bigger and more loosely attached flocs, microflocs were invariably observed, and their formation correlated positively with flow energy. The characterization of effective particle sizes between ingressed and suspended sediments demonstrated that, although the particle size distributions had similar modalities for both sediment types, ingressed sediment was coarser than suspended particles – demonstrating that interstitial flocculation can occur, even though it is also likely that coarser flocs are preferentially ingressed in the channel. Field measurements of ingress demonstrated that, for flocculated particles, ingress was predominantly vertical during higher energy flows, while horizontal mechanisms of accumulation were more important during lower energy flow conditions. The model application estimated that ~60 % of the upstream suspended sediment gets trapped in the channel framework over the ~10 km study reach. Although we lack independent means to validate these findings in the field, given the nearly continuous sediment supply from diffuse sources along the catchment, the fine sediment ingress rate recorded in an annular flume was well within the range of ingress rates measured in the field, which supports the validity of the modelled estimates. Despite high accumulation rates, field observations

demonstrated that no sites were saturated or clogged with fine sediments during the field campaigns. The observations reported in this study bring some novel perspectives to the understanding of flocculation and ingress processes of cohesive solids in a gravel-bed river (i.e., in-situ flocculation mechanisms of suspended and ingressed particles, floc size effects on the ingress process, and the modelling framework of the propagation and storage of cohesive particles). The reported results also indicate the potential for future investigations on the role of the interstitial load for fine sediment storage and possible exfiltration mechanisms driven by groundwater upwelling. Given the importance of cohesive sediment as a vector for contaminant and nutrient transport and the limited capacity for interstitial flushing of fines, gravel-bed rivers may delay the downstream impacts of upstream disturbances (legacy effects) for decades. Accordingly, due to the increasingly reported deleterious impacts of excess cohesive sediment in gravel-bed streams, advancing knowledge on the propagation and storage of fine sediment, as proposed in this study, is imperative for its strategic management and prevention.

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Dedication

To my mother, Maria Alice de Freitas.

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who was just so proud of me for being in environmental sciences,
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Chapter 1. General introduction

1.1. Problem statement

Gravel-bed rivers draining forested headwater regions are critically important for the provision of high-quality water (Emelko et al., 2016, 2011) and for biodiversity and landscape-scale ecological integrity (Hauer et al., 2016). The forested soils in these landscapes promote the infiltration of precipitation, limiting the generation of surface runoff and erosion processes (Neary et al., 2009). Further, water infiltration into forested soils allows the occurrence of natural filtration processes, in which leaching nutrients and potential contaminants can be assimilated by vegetation or immobilized and degraded by the soil and soil biota (Keesstra et al., 2012). Despite their importance, these regions have been increasingly impacted by natural (climate change-exacerbated) and anthropogenic landscape disturbances that generally increase the hillslope-channel connectivity and accelerate the delivery of fine sediment to receiving streams (Goode et al., 2012; Owens et al., 2005). Fine sediments, generally defined as particles with diameters <2 mm, can be further operationally distinguished by grain size into non-cohesive and cohesive (organic and inorganic particles <63 μm) solids. Cohesive solids have electrochemically active surfaces that allow these particles to flocculate with other particles within the flow field, forming flocs (Droppo and Ongley, 1992; Lick et al., 1992; Partheniadis and Kennedy, 1966). Further, cohesive solids can adsorb pollutants such as metals, phosphorus, and organic compounds (Allan, 1986; Horowitz and Elrick, 1987; Ongley et al., 1992) and, as such, are key vectors for the transport and fate of pollutants in the environment.

In undisturbed landscapes, natural erosion processes of fine sediment contribute to the development of ecological (Buffington and Montgomery, 1999; Collins et al., 2011; Collins and Zhang, 2016) and morphological (Brunke, 1999; Montgomery and Buffington, 1998; Perret et al.,

2018) river functions. In contrast, elevated levels of cohesive materials, generally mobilized from landscape disturbances, can cause deleterious physical, chemical, and biological impacts on river systems. In the water column, excess fine sediment can increase turbidity, damage habitats, alter primary productivity, increase sedimentation, and compromise water quality and drinking water treatability (Chapman et al., 2014; Emelko et al., 2011; Jones et al., 2014; Kemp et al., 2011). In the channel bed framework, excess interstitial fine sediment can clog interstitial pores and decrease permeability, hydraulic conductivity (Brunke, 1999; Schälchli, 1992), and hyporheic exchanges of dissolved oxygen, nutrients, and metabolic waste products from aquatic organisms (Packman and MacKay, 2003; Wharton et al., 2017). Excess interstitial fine sediment in the gravel-bed framework has detrimental impacts on benthic habitat, affecting spawning sites and egg development of lithophilic fish species (Chapman et al., 2014; Greig et al., 2005; Kemp et al., 2011). It can also lead to the burial of benthic and phytobenthic organisms (Jones et al., 2014, 2012b, 2012a; Wood and Armitage, 1997). Further, excess levels of interstitial cohesive sediment have been reported to increase bed stability (Barzilai et al., 2013; Perret et al., 2018), ultimately limiting the flushing capacity of gravel-bed rivers (Schälchli, 1992).

Despite the relatively well-documented impacts of excess fine sediment delivery to receiving waters, several emerging issues and knowledge gaps still exist regarding the transport and fate of cohesive sediments. Flocculation processes can alter the transport properties of flocs in comparison to primary particles by increasing their effective (flocculated) particle sizes, changing their density, porosity, and settling velocity (Droppo, 2001; Droppo and Ongley, 1992; Mehta and Partheniades, 1975; Petticrew and Biickert, 1998; Williams et al., 2008). Among these morphological changes, effective size is a critical parameter for evaluating transport properties since it is a directly measurable attribute and it can be related to other attributes, such as density and settling velocity

(Droppo and Krishnappan, 2016; Lau and Krishnappan, 1997). However, the investigations of flocculation processes have considerably focused on lacustrine, coastal, and engineered environments (see Droppo et al., 2005a) relative to freshwater riverine environments. Earlier observations on riverine flocculation processes through effective (flocculated) particle size distributions have been observed through microscopy and image analysis (e.g., Droppo et al., 2005b; Petticrew and Biickert, 1998; Stone and Droppo, 1994), but such assessments are constricted to ex-situ analysis and inherent methodological limitations such as the limited sample size of such measurements. More recently, technological advances using *in-situ* laser-diffraction particle size analyzers (i.e., Laser *In-Situ* Scattering and Transmissometry – LISST) have permitted the *in-situ* observation of these flocculated particle size distributions. However, even with such technological advancements, only a relatively low number of field studies have been conducted to assess riverine flocculation properties (de Lange et al., 2024; Livsey et al., 2022; Upadhayay et al., 2021; Williams et al., 2007), and this assessment is even more scarce in high-energy, mountainous gravel-bed rivers (Stone et al., 2021b). To the best of my knowledge, and despite the importance of high-energy gravel-bed rivers, as discussed above, no studies have yet measured *in-situ* flocculated particle size distributions at large spatial and temporal scales to assess large-scale effects of flocculation on the transport of cohesive particles in these river systems.

Further, despite the reported deleterious impacts of excess fine sediment interstitial accumulation, studies regarding such channel storage have been predominantly conducted in lowland, lower energy gravel-bed rivers (e.g., Collins and Walling, 2007a, 2007b; Harper et al., 2017; Lambert and Walling, 1988; Naden et al., 2016; Walling et al., 2003). Previous studies in these lower-energy riverine systems have reported uncertainties associated with the methodological assessment of ingress rates (Harper et al., 2017). However, these methodological

ingress measurement assessments have not been done in high-energy gravel-bed rivers, and no studies have assessed the variability associated with different designs of ingress samplers. Further, in higher flow energy environments, the investigation of fine sediment ingress under turbulent flow conditions has been mostly regarding the storage of non-cohesive particles (Beschta and Jackson, 1979; Brunke, 1999; Casas-Mulet et al., 2017; Wooster et al., 2008). To a lesser extent are the studies assessing the ingress properties of cohesive particles, and such interstitial accumulation in gravel-bed frameworks has been predominantly assessed under laboratory flume conditions (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018; Shrivastava et al., 2020). To the best of my knowledge, no studies have assessed relationships between hydro-sedimentological drivers and the ingress of cohesive particles through the *in-situ* assessment of their flocculated particle size distributions. Further, no other studies have reported on the relationships between flocculated particle size distributions of suspended and interstitial groups of cohesive sediments in gravel-bed rivers.

Finally, a considerable body of research has investigated riverine cohesive sediment transport properties using the rotating annular flume (Table 6.2). These studies are critical for assessing and parametrizing cohesive sediment transport under a controlled environment. However, no other studies have reported observations on effective particle size distributions of site-specific sediment from the Crowsnest River through deposition, erosion, and ingress flume assessments. Most importantly, no other studies have related these findings to field observations. Additionally, despite existing research that has applied the cohesive sediment transport model RIVFLOC (Droppo and Krishnappan, 2016; Krishnappan, 2022; Stone et al., 2021b), comparisons between modelled and field observations have thus far relied on small field datasets. This limitation hinders the advance of the current understanding of cohesive sediment dynamics.

Accordingly, the integration of a robust field dataset, flume observations, and model predictions is required to address this research gap.

Given the paucity of information and the complexity of processes on the effects of turbulence on the nature of flocs (i.e., settling velocity, particle size, critical shear stress for deposition and erosion) and the subsequent effects on their interstitial accumulation, most fine sediment transport models do not include terms describing flocculation and ingress processes in gravel-bed rivers. In turn, fine sediment transport models might inaccurately estimate the propagation of these particles within these river systems, which has important consequences for land managers in assessing the fate and potential impacts caused by diffuse pollution sources from upstream landscape disturbances. Accordingly, given the aforementioned research gaps found in the literature, quantifying flocculation and ingress processes through robust field and laboratory conditions is required to advance and refine cohesive sediment transport models used to assess the storage and propagation of these solids in gravel-bed rivers.

1.2. Research objectives

Given the research gaps discussed above, the primary goal of this thesis was to evaluate the physical aspects of flocculation and ingress processes and their effects on the propagation and storage of cohesive solids in a gravel-bed river through laboratory, field, and modelling approaches. The specific objectives to achieve this goal (Figure 1.1) were identified as:

- Chapter 2: Characterize *in-situ* flocculation properties of suspended solids at different reaches of a gravel-bed river during spring freshet and stormflow conditions through the assessment of multimodal effective particle size distributions.

- Chapter 3: Critically evaluate and compare different designs of sediment trap samplers commonly used to measure fine sediment ingress and direction (vertical and horizontal) of accumulation in gravel-bed rivers.
- Chapter 4: Examine the hydro-sedimentological drivers of fine sediment ingress in a gravel-bed river.
- Chapter 5: Characterize flocculation properties of suspended sediments in a rotating annular flume under different bed configurations for a range of flow conditions through deposition, ingress, and erosion experiments.
- Chapter 6: Calibrate a semi-empirical fine sediment transport model (RIVFLOC) that incorporates flocculation and ingress data from field and laboratory investigations to evaluate the potential mechanisms controlling fine sediment transport and fate in a gravel-bed river.

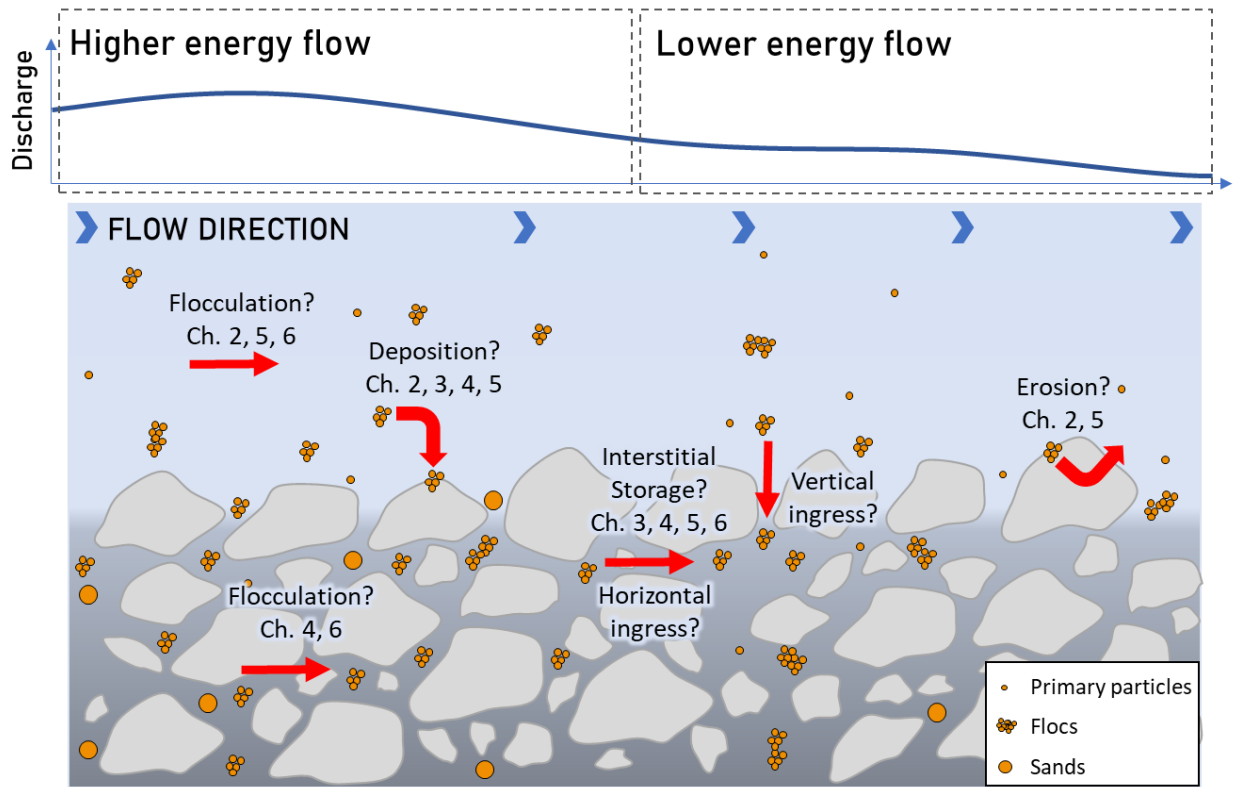


Figure 1.1. Components of the fine sediment transport nexus investigated in this thesis and the corresponding chapters in which such components were assessed.

1.3. Research approach and thesis structure

This thesis is composed of 7 Chapters that describe the field, laboratory, and modelling assessments performed to evaluate flocculation properties and their effects on the propagation and storage of cohesive solids in the study gravel-bed river (Figure 1.2). In Chapter 2, *in-situ* particle size distributions of suspended solids, measured with a LISST-200x, were assessed at different flow conditions in four sites of the Crowsnest River to characterize flocculation processes and the implications for the transport of suspended particles (Maltauro et al., 2023). In Chapters 3 and 4, >250 sediment traps, consisting of three designs of samplers, were deployed in triplicates at four

downstream locations in the Crowsnest River to assess vertical and horizontal mechanisms of interstitial accumulation of cohesive and non-cohesive fine sediment (<2 mm). Chapter 3 used the sediment trap results to critically evaluate and compare the methodological approaches commonly used to measure interstitial fine sediment accumulation (Maltauro et al., 2024b). In Chapter 4, mean flow hydraulic parameters derived from the MOBED flow model and measured suspended sediment (mass and volume) concentrations were assessed to identify hydro-sedimentological drivers of interstitial accumulation according to particle size (Maltauro et al., 2024a). In Chapters 5 and 6, deposition, ingress, and erosion experiments were conducted using fine sediments from the Crowsnest River in a rotating annular flume. In Chapter 5, particle size distributions measured through each flume experimental setting were characterized to assess flocculation properties (Maltauro et al., 2024c). In Chapter 6, flume results were used to calibrate and validate a fine sediment transport model (RIVFLOC), which was then applied and compared to the dataset measured *in-situ*. Finally, in Chapter 7, a synthesis of the main findings from this thesis is presented, and recommendations for future investigations are proposed.

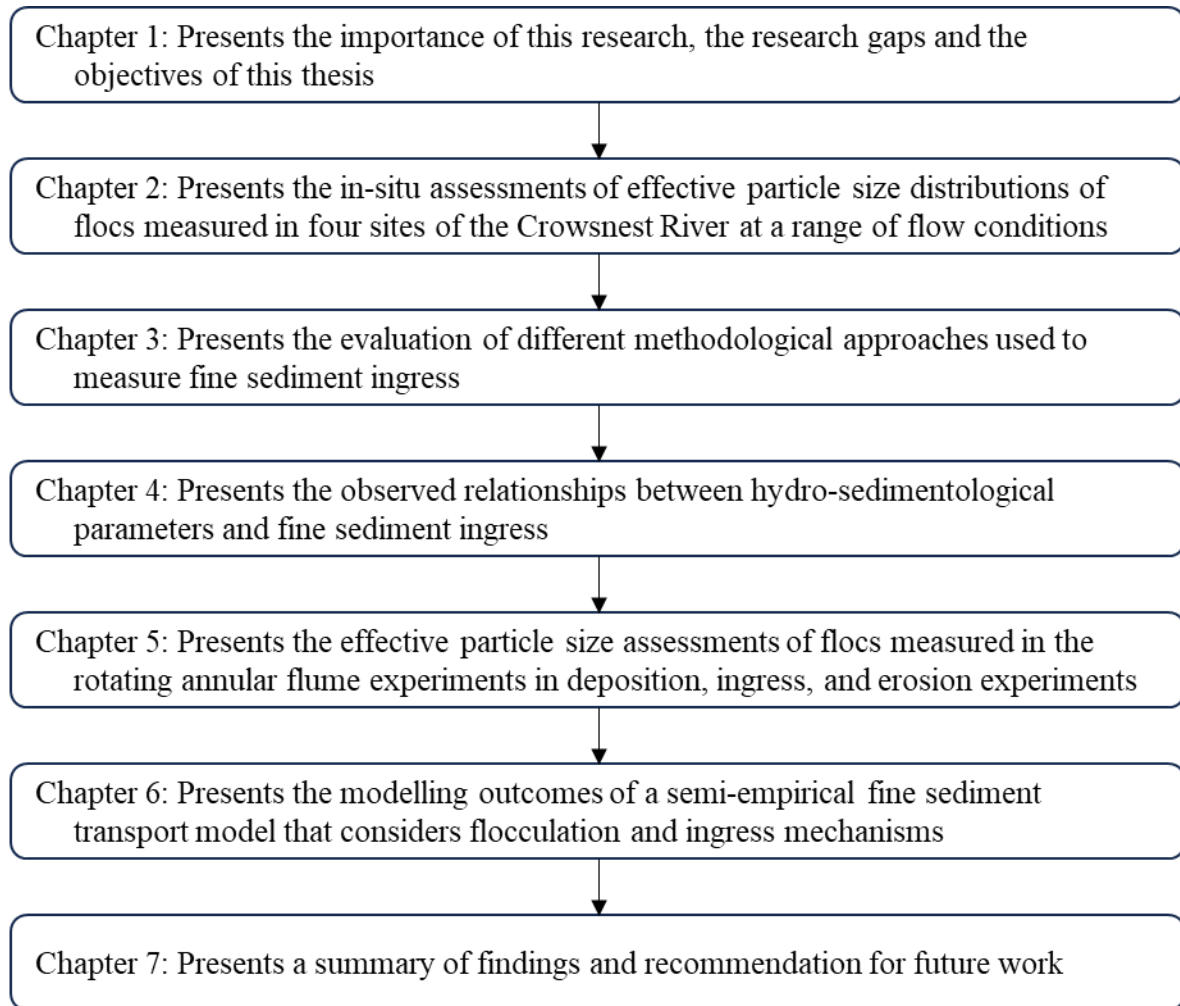


Figure 1.2. Outline of thesis structure and relevance of each chapter.

Chapter 2. The effect of shear-dependent flocculation on the multimodality of effective particle size distributions in a gravel-bed river during high flows

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2.1. Summary

Flocculation and particle breakage occur simultaneously within turbulent flow fields, and while such observations have been made in estuarine and salt-water environments, few studies have been conducted in riverine environments. These dynamic processes occur because flocs of different sizes form under varying flow conditions through different attachment mechanisms, which, under the same turbulent condition, might lead to the formation of certain flocs but to the breakage of others. These shear-dependent particle interactions lead to multimodal effective particle size distributions, which can be used to assess *in-situ* flocculation processes. In Chapter 2, particle size distributions of suspended solids were assessed according to flow conditions in four sites of the Crowsnest River to assess flocculation processes. Fine ($<500\ \mu\text{m}$) suspended sediments were predominantly transported as flocs, even during the highest observed shear stresses. When high shear stresses occur, flocs break into relatively smaller flocs rather than disaggregating into primary particles, which suggests the higher attachment strength of smaller relative to coarser flocs. Further, while the biggest flocs ($\sim 200 - 500\ \mu\text{m}$) were observed to break at the highest shear stresses, increasing shear stresses promoted the formation of flocs within the size class range ($\sim 25 - 200\ \mu\text{m}$). These observations demonstrate that, despite the turbulent flow, flocculation was

imperative for the transport of suspended fine sediment and that the different attachment strengths should be incorporated into existing modelling frameworks.

2.2. Introduction

‘Excess’ suspended particulate matter (SPM) in rivers is a key driver of water quality degradation (Bilotta and Brazier, 2008; Brunke, 1999; Wood and Armitage, 1997). SPM is an important pollutant vector (Collins et al., 2005; Stone and Mudroch, 1989; Walling et al., 2003) that can affect aquatic ecosystem health (Jones et al., 2012b; Kemp et al., 2011; Wilkes et al., 2019) and challenge water treatability and the provision of safe drinking water (Bladon et al., 2014; Emelko et al., 2011). Early research on fluvial SPM assumed that particulate matter was primarily transported as individual particles and interaction with the channel bed was limited (Einstein et al., 1940; Krishnappan, 2007; Walling and Collins, 2016). However, it is now more commonly accepted that cohesive solids ($<63\ \mu\text{m}$) are mainly transported as flocculated particles due to the geochemical and related electrochemical surface properties of these materials (Droppo and Krishnappan, 2016; Krishnappan, 2007; Lai et al., 2018; Lick, 1982; Lick et al., 1992; Williams et al., 2008). These aggregated particles formed in the water column, known as flocs, typically consist of a complex mixture of inorganic (e.g., clays and silts) and organic (e.g., extracellular polymeric substances – EPS) particles as well as microbial organisms (Droppo, 2001; Ho et al., 2022). Further, soil aggregates formed on the land surface can eventually reach the water column and be quickly incorporated to SPM, forming hybrid soil aggregate-floc particles (Droppo et al., 2005b). Floc composition can influence the morphology (e.g. floc size) and transport properties of aggregated particles, and both these attributes have been observed to have high spatial and temporal variability in rivers (Petticrew, 2005; Phillips and Walling, 2005).

The need for improved knowledge of flocculation and SPM transport processes in gravel-bed rivers draining forested mountainous landscapes has emerged as a critical research area. These rivers often drain forested landscapes that are critical for source water supply (Emelko et al., 2011; Stone et al., 2021b), regional biodiversity and landscape scale ecological integrity (Hauer et al., 2016). However, there is increasing concern regarding anthropogenic and natural landscape disturbances such as harvesting, wildfire, municipal wastewater discharge, agriculture and drought (Emelko et al., 2011; Flannigan et al., 2009; Schindler and Donahue, 2006; Watt et al., 2021), which increases the delivery of ‘excess’ fine particulate matter from hillslopes to stream networks. The boundary shear stress conditions in gravel-bed rivers influence fine sediment transport dynamics via intra-gravel infiltration and exfiltration mechanisms (Casas-Mulet et al., 2017). Such mechanisms permit the temporary storage of fine sediment in gravel-beds, which can influence nutrient and contaminant fluxes (Walling and Collins, 2016) and salmonid spawning habitats (Collins et al., 2014; Sear et al., 2014). Despite the widely reported deleterious impacts of ‘excess’ SPM and even more recent advances in understanding the role of natural flocculation processes on these impacts, the factors controlling flocculation and its effects on the transport and fate of SPM in gravel-bed river systems still require further study (Krishnappan, 2022; Mikkelsen et al., 2006). Such information is required to refine the flocculation component of fine sediment transport models in these river systems (Koiter et al., 2015; Petticrew, 2005; Stone et al., 2021b).

Flocs are created under different conditions of fluid shear by the dynamic interaction of particle types such as primary particles, flocculi, microflocs and macroflocs (Lee et al., 2012). Primary particles can aggregate into tightly packed flocs referred to as flocculi (Lee et al., 2012). Under favorable biophysical conditions, these particles combine with other flocculi to form microflocs that can grow into more loosely-bound macroflocs (Eisma, 1986; Ho et al., 2022; Lee

et al., 2012; Mikkelsen et al., 2006). Flocculi are formed by strong Coulombic attraction between negatively charged clay surfaces and sporadic positive sites at the edge of these minerals (face-to-edge attachment) and these particles seldom disaggregate into primary particles (Lee et al., 2012). In contrast, micro and macrofloc assemblages form due the presence of extracellular polymeric substances (EPS), which can lower the resistance of flocs to breakage (Droppo, 2001; Ho et al., 2022). In a fluid shear, flocculation and particle breakage coexists interactively, causing particle size distributions (PSDs) to be dynamic (Gibbs et al., 1989; Le et al., 2020; Phillips and Walling, 1999). Accordingly, PSDs are often multimodal, presenting multiple modal peaks (Lee et al., 2012; Mikkelsen et al., 2006; Stone and Krishnappan, 2003), and lognormal, with skewness depending upon the dominant size classes in suspension (Blott and Pye, 2001; Lee et al., 2012).

Floc size is a critical parameter controlling the transport and fate of SPM. The hierarchical assemblage from primary particles to macroflocs changes particle size, shape, structure, and density (Ho et al., 2022), ultimately affecting the deposition and the downstream propagation of suspended particles (Droppo, 2001; Krishnappan, 2007; Maerz et al., 2011). Despite extensive research on flocculation in both engineered and natural systems (Droppo et al., 2005a), advancing knowledge of flocculation in environments undergoing cumulative development pressures is required to refine fine sediment transport models (Krishnappan, 1991; Stone et al., 2021b). Time-varying multimodal PSD data have been used previously to understand possible controls and to investigate particle and aggregate dynamics in coastal and estuarine waters (Gibbs et al., 1989; Le et al., 2020; Lee et al., 2012; Mikkelsen et al., 2006). Here, we adopt this approach to evaluate multimodality in the effective particle sizes distributions (EPSDs) of SPM in a gravel-bed river under varying conditions of fluid shear and SPM concentrations at a range of spatial and temporal scales. The specific objectives of this study were to: 1) evaluate changes in discrete groups of

particles and aggregates (primary particles, flocculi, microflocs and macroflocs) as a function of SPM volume concentration (VC), discharge (Q) and bed shear stress (τ) during spring freshet and stormflow, and; 2) characterize the spatial and temporal variability in EPSD multimodality caused by the mixing of multiple particle and aggregate size groups under flocculation and erosion/resuspension. The investigation of spatial and temporal EPSD multimodality, in situ, is critical for the refinement of SPM transport models, which can ultimately benefit watershed management by improving estimates of the transport and fate of sediment and associated contaminant in downstream aquatic environments.

2.3. Materials and methods

2.3.1. Site description

The Crowsnest River drains an area of $\sim 679 \text{ km}^2$ on the eastern slopes of the Rocky Mountains in southwestern Alberta. The headwaters of this river originate in the upper montane snowmelt-dominated regions that drain into Crowsnest Lake (1357 m.a.s.l.). The river flows through the Municipality of Crowsnest Pass and then into the Oldman Reservoir (1113 m.a.s.l.) (Watt et al., 2021). Average annual precipitation ranges from ~ 400 to $1000 \text{ mm year}^{-1}$ and $\sim 30\%$ is snow fall (Alberta Agriculture, Forestry and Rural Economic Development and Alberta Climate Information Service (ACIS), 2021). Streamflow in the Crowsnest River is strongly influenced by snowmelt, which occurs between the late spring and early summer seasons, typically peaking in early June (Waterline, 2013). Peak flows occur due to rain-on-snow events, or in response to large convective or frontal storms in the summer (Stone et al., 2014). Baseflow in the Crowsnest River, however, is dominated by groundwater inputs from alluvial aquifers in the river valley (Waterline, 2013). Regional geology consists of limestone, dolomite, shales, mudstones, and fine-grained

sandstone, while surficial geology comprises thin colluvium, fine-grained till blankets and till veneers (Silins et al., 2014; Stone et al., 2014). Glacial deposits in the study basin are potential sources of fine-grained materials that enter river channels either through hillslope surface or channel bank erosion veneers (Silins et al., 2014; Stone et al., 2014).

2.3.2. Sampling programme

The study was conducted at four locations along a 10 km reach of the Crowsnest River (Figure 2.1) that represent a continuum of cumulative impacts from both natural and anthropogenic disturbances in the Crowsnest River Basin. Land disturbance types in the watershed include agriculture, industry, mining, municipal development and wildfire and these pressures cumulatively increase downstream in lower reaches (S5 and S7) of the Crowsnest River (Watt et al., 2021). A detailed description of geology, land use and landscape disturbance in the Crowsnest River basin are presented in Watt et al. (2021). Hydrometric and sediment sampling programmes were conducted from May 22nd to August 2nd, 2019, to measure instantaneous discharge, VC and EPSD of suspended solids during three high discharge events at four study sites in the Crowsnest River (Figure 2.1). Event 1 occurred during the late spring freshet, while events 2 and 3 were generated by rainfall. Both the EPSD and VC of suspended solids ($< 500 \mu\text{m}$) were measured in the centroid of flow with a LISST-200x (Sequoia Scientific, Bellevue, WA, USA) at intervals of approximately 3 to 4 days. The LISST-200x operates on a laser diffraction principle that provides lognormal particle size distributions over 36 size bins that range from 1 to $500 \mu\text{m}$ (SEQUOIA Scientific Inc. 2018). Measurements of the EPSD and VC of SPM were made at each of the four sites for a period of 3 minutes, in which the LISST-200x was configured to sample every second thus producing >100 measurements for each deployment. Total suspended solids (TSS) was

measured following the Standard Methods Procedure (APHA, 1995), and the suspended sediment load was calculated according to the discharge-weighted TSS method (Nava et al., 2019). In this study, because *in-situ* sediment concentration was measured through laser diffraction, values of TSS were only used to calculate sediment load and specific sediment yield. Instantaneous discharge at each site was either measured with a Swiffer current velocity meter (Model 2100) using the area-velocity method or obtained from gauging stations deployed by the Southern Rockies Watershed Project (SRWP; Silins, unpublished data). A comparison of flow measurements immediately downstream of S7 at Environment Canada Gauging Station (05AA008@Frank) and at Site 7 for the study period is presented in Figure 2.2. A calibrated flow model (MOBED) (Krishnappan, 1981) was used to provide estimates of bed shear stress in the Crowsnest River. MOBED is an unsteady and mobile boundary one-dimensional river flow model (Krishnappan, 1981). Input data to MOBED consisted of the cross-sectional geometry of each transect (measured every ~500 m along the 10 km reach), initial bed and water surface elevation, boundary conditions at the first upstream and last downstream transects, and bed roughness parameters (Stone et al., 2021b) (See Appendix A).

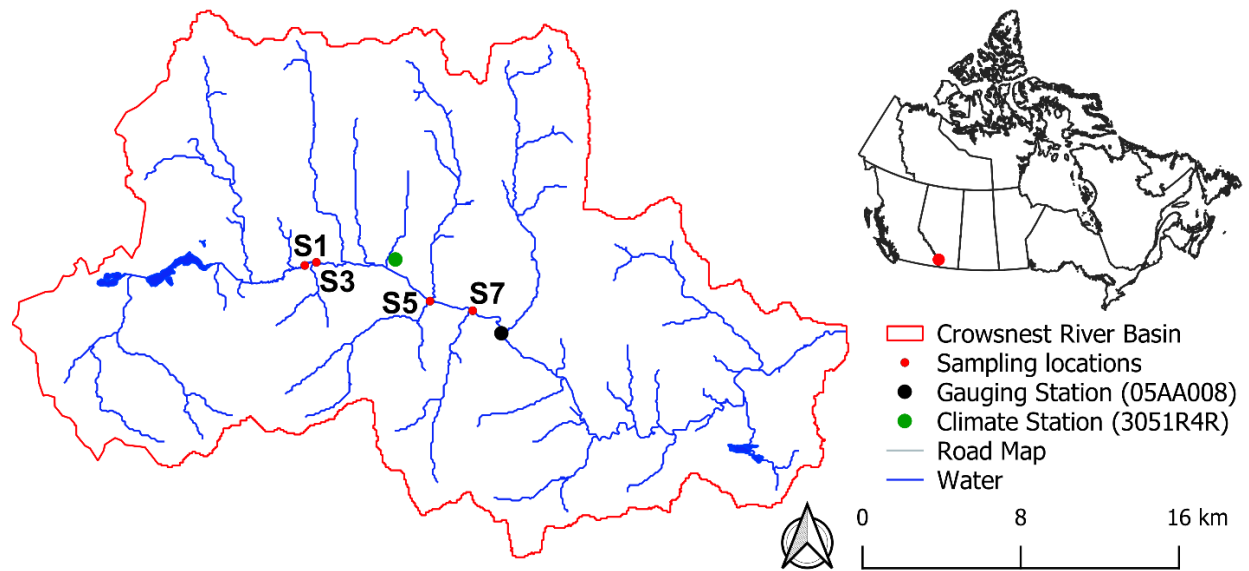


Figure 2.1. Location of study sites in the Crowsnest River basin.

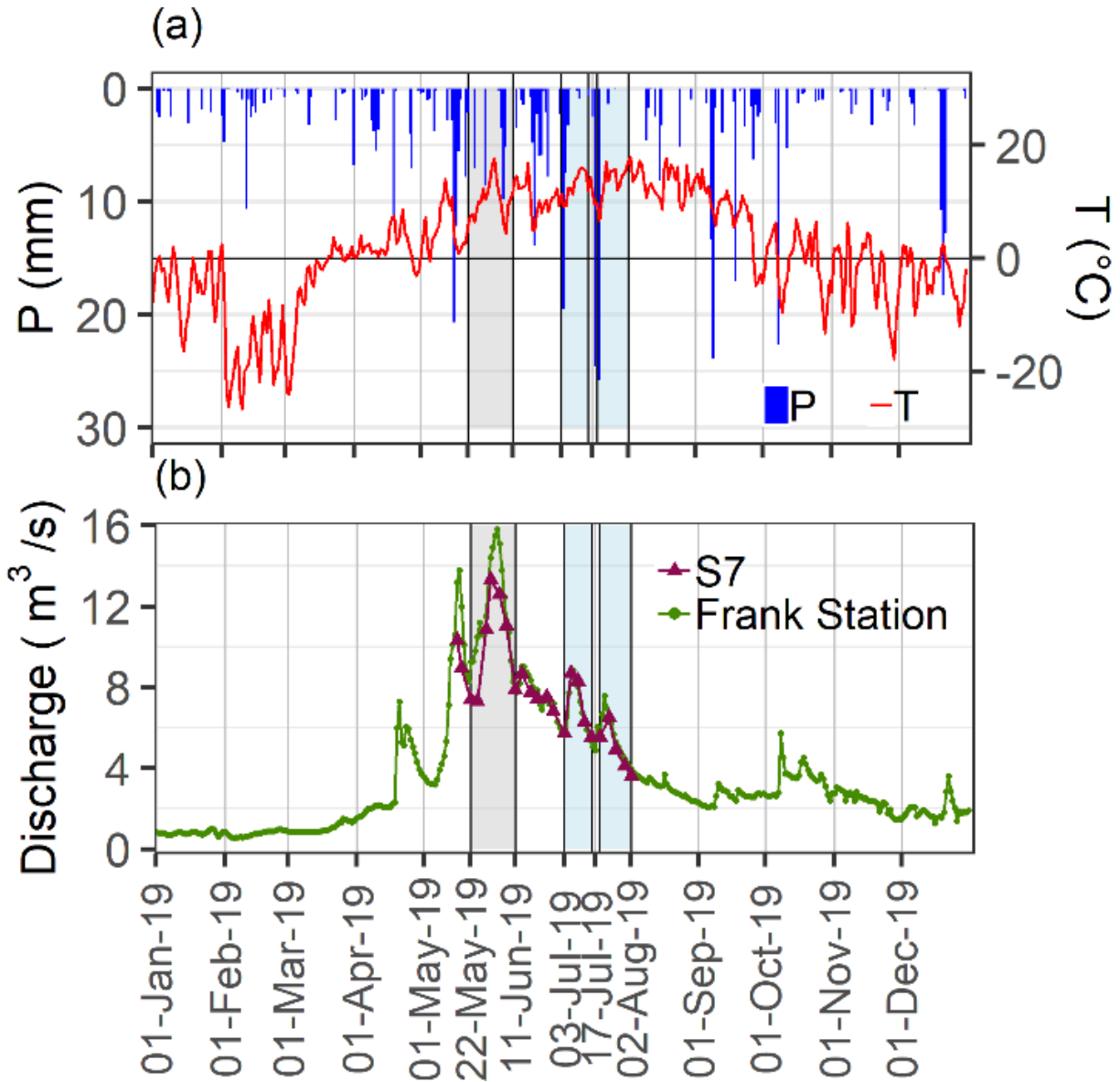


Figure 2.2. a) Daily cumulative precipitation and daily mean temperature at the Crowsnest station (3051R4R) (Alberta Agriculture, Forestry and Rural Economic Development and Alberta Climate Information Service (ACIS), 2021); b) daily mean values of discharge at the Crowsnest River – Frank (05AA008) Gauging Station (Environment Canada, 2021), and instantaneous discharge measurements at S7 during the study period (burgundy line). Shaded areas in gray represent Event 1, and those in blue Events 2 and 3.

2.4. Analysis of particle populations

Multimodality of suspended solids PSDs and their VC were evaluated using the conceptual flocculation scheme proposed by Lee et al. (2012). Accordingly, LISST-200x data were separated into five relevant particle size fractions: 1) primary particles ($1.0 \leq D < 4.7 \mu\text{m}$), 2) flocculi ($4.7 \leq D < 24.6 \mu\text{m}$), 3) microflocs ($24.6 \leq D < 212.0 \mu\text{m}$) and 4) macroflocs ($212 \leq D \leq 500 \mu\text{m}$). The grouping in such size classes is performed based upon the *in-situ* observed EPSD of SPM. Hence, if silt and sand-sized individual grains $> 4.7 \mu\text{m}$ were occurring in suspension, these particles would have been classified and included in the corresponding flocculated size class. However, beyond the observations performed in our discussions (section 3.1), photomicrographs taken throughout the study period (Maltauro, unpublished data) demonstrate that individual particles $> 4.7 \mu\text{m}$ are seldom transported in suspension at the study sites. Although the precise definition of thresholds for size classes can be rather arbitrary (Mikkelsen et al., 2006), our thresholds were defined according to the modal peaks observed in the EPSD data (Figure 2.3). Spatial variability between upstream and downstream reaches was assessed with the Wilcoxon rank sum test (Kassambara, 2021), while temporal variability between the three events was assessed using the Kruskal-Wallis and post hoc pairwise Dunn's test with Benjamini-Hochberg (BH) false discovery rate correction for multiple comparisons (Kassambara, 2021). All plots were created using ggplot2 R package (Wickham, 2016). Principal component analysis (PCA) was performed for data reduction, to identify key controls on the variance in the EPSDs. All statistical analysis were performed using R Statistical Software (R Core Team, 2022) through RSudio Integrated Development Environment (RStudio Team, 2022).

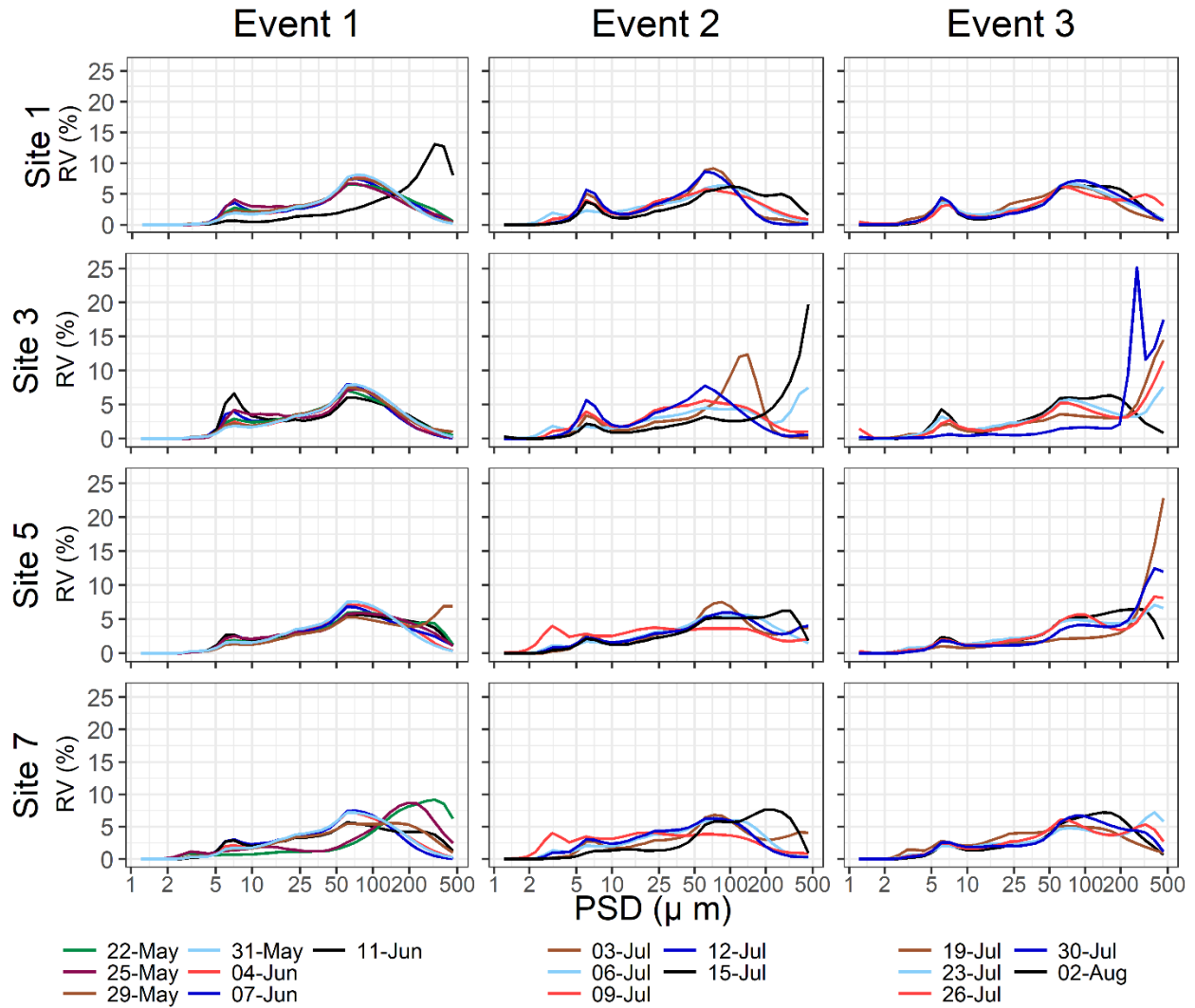


Figure 2.3. Temporal variability in the Effective Particle Size Distributions (EPSDs) of suspended solids in the Crowsnest River during three high discharge events for the four study sites.

2.5. Results and discussion

2.5.1. Shear dependent flocculation and multimodality in size distributions

Spatial and temporal variability in the EPSD of SPM for three high flow events in the Crowsnest River are presented in Figure 2.3. River discharge, bed shear stress, VC and specific sediment yield for each discharge event are summarized in Table 2.1. The EPSDs of SPM in river

systems under varying flow conditions can be highly variable in time at high resolutions (Williams et al., 2007), which is in agreement with data observed in the Crowsnest River. Here, as per other studies (Lee et al., 2012; Mikkelsen et al., 2006; Williams et al., 2007), the EPSDs are presented as averages of the >100 measurements taken during ~3 minutes at each site. Outlier values were not discarded in order to account for the natural variability in EPSDs (see Appendix A). The relative volumes of these averaged EPSDs can be observed in Figure 2.3. Relative standard deviation (RSD) was calculated for each averaged EPSD pertaining to each size bin, and the overall average RSD (average RSD = $\sqrt{(RSD_1^2 + RSD_2^2 + \dots + RSD_k^2)/k}$, where k represents the 36 size bins for each deployment) for all deployments (k=2448) was ~245%. EPSDs were multimodal, commonly consisting of two modal peaks (Figure 2.3). The first modal peak was consistently observed between 5 and 10 μm , while the second modal peak occurred between 50 and 100 μm . In some cases, there were shifts to larger size classes during lower discharge conditions for events 2 and 3. The first modal peak represents flocculi size fractions, which are the building blocks of coarser flocs (Mikkelsen et al., 2006; Stone and Krishnappan, 2003). Representative images of various particle size fractions (primary particles, flocculi, microflocs and macroflocs) are shown in photomicrographs of suspended solids from the Crowsnest River (Figure 2.4)

Table 2.1. Variability in river discharge, shear stress, volume concentration and specific suspended sediment yield for three discharge events in the Crowsnest River.

	Event 1				Event 2				Event 3			
	S1	S3	S5	S7	S1	S3	S5	S7	S1	S3	S5	S7
Initial Q ($\text{m}^3 \text{s}^{-1}$)	3.8	4.2	5.2	7.4	4.5	4.7	5.2	5.8	4.1	4.2	4.6	5.5
Peak Q ($\text{m}^3 \text{s}^{-1}$)	8.7	9.4	11.2	13.3	5.5	5.8	6.8	8.7	4.4	4.5	4.9	6.5
Average Q ($\text{m}^3 \text{s}^{-1}$)	6.0	6.5	8.0	10.1	4.7	4.9	5.5	6.9	3.8	4.0	4.3	4.9
¹Difference in Q ($\text{m}^3 \text{s}^{-1}$)	4.8	5.3	5.9	6.0	1.5	1.7	2.2	3.1	1.1	1.1	1.3	2.9
Initial τ (Pa)	26.2	22.2	16.9	22.6	28.7	24.3	18.4	23.8	27.1	23.1	17.7	23.1
Peak τ (Pa)	42.2	35.6	23.9	33.3	33.7	29.6	24.1	33.7	28.2	23.9	20.7	27.3
Average τ (Pa)	33.6	28.3	20.5	27.1	29.7	25.4	19.6	25.9	26.2	22.3	17.9	23.2
¹Difference in τ (Pa)	16.0	13.4	7.0	10.7	6.9	6.8	6.5	11.2	3.8	3.1	4.5	6.5
Initial VC ($\mu\text{L L}^{-1}$)	20.5	15.9	19.7	25	6.8	9.3	10.7	10.7	8.1	12.5	25.5	10.5
Peak VC ($\mu\text{L L}^{-1}$)	46.5	41.7	51.8	42.3	14.9	14.3	24.7	22.7	8.6	34.2	25.5	13.3
Average VC ($\mu\text{L L}^{-1}$)	26.4	22.7	30.6	25.8	8.9	9.9	15.0	12.4	8.1	14.6	15.5	11.0
^aDifference in VC ($\mu\text{L L}^{-1}$)	36.2	30.9	34.7	28.4	9.2	8.8	14.0	18.1	1.2	26.7	14.5	3.9
Sediment Load (t)	69.1	92.6	113.1	109.5	42.1	90.0	63.7	47.2	22.1	13.3	21.8	20.0
Specific sed. Yield (Kg Km^{-2})				271.64				117.01				49.53

^aDifference between maximum and minimum observation.

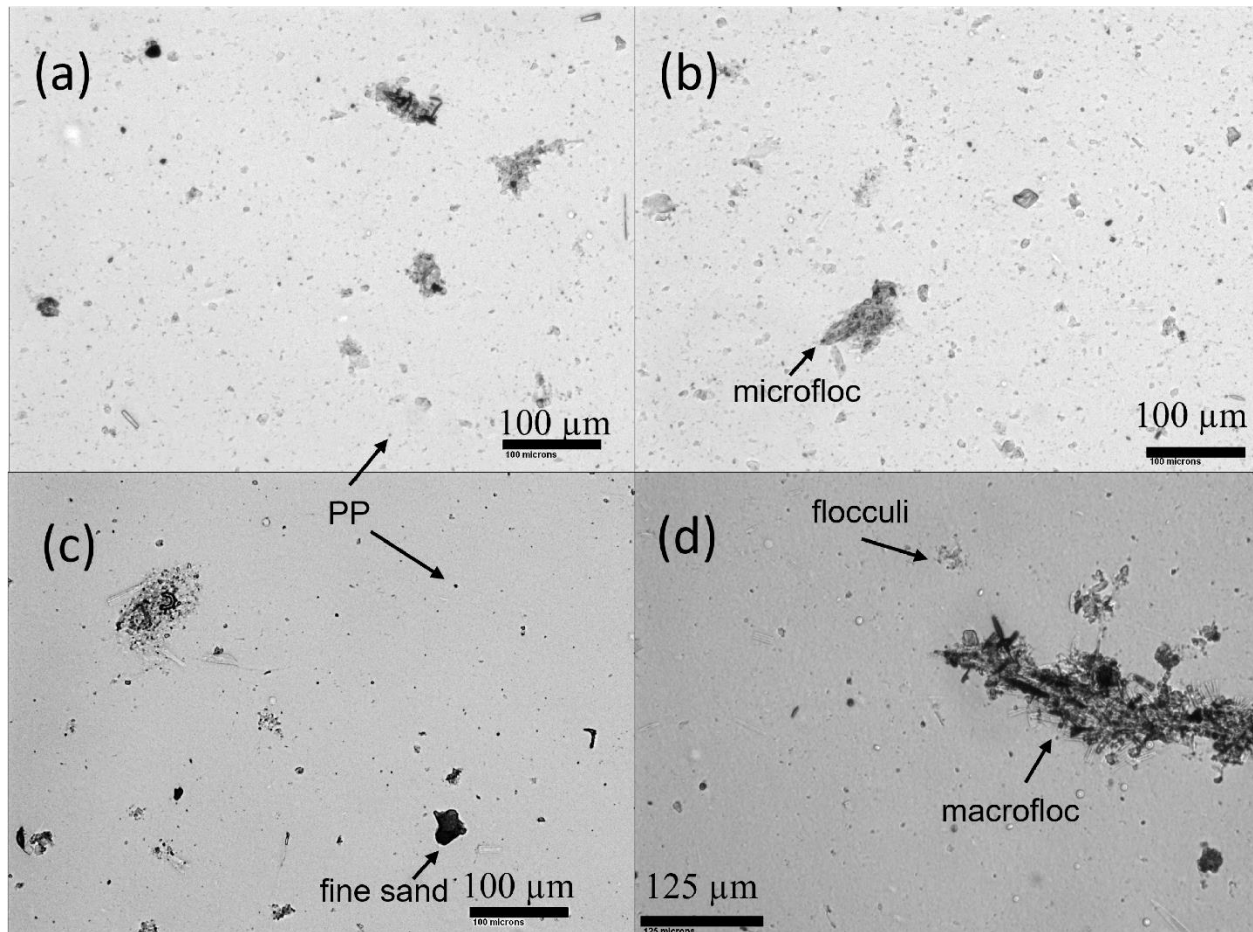


Figure 2.4. Photomicrographs of primary particles (PP) and floc classes in the Crowsnest River: A) Site 5 on July 9th; B) Site 7 on July 9th; C) S5 on May 29th; and D) Site 7 on July 30th.

To assess flocculation dynamics in the Crowsnest River, hydraulic (discharge and bed shear stress), and SPM (VC, particle diameters and size classes) variables were plotted as a time series for each site (Figure 2.5). Differences in discharge and bed shear stress were the highest at all sites during event 1, except at site 7, at which the difference in shear stress was the highest during event 2 (Table 2.1). Increases in VC were generally well aligned with increases in discharge and shear stress in events 1 and 2, but responses of VC to discharge in event 3 varied at all sites (Figure 2.5). Absolute (FC), relative (RV), and cumulative (CV) concentrations of microflocs were consistently predominant in event 1, but those were surpassed by macrofloc concentrations for some

measurements of events 2 and 3 (Figure 2.5). The flocculi class did not exceed either the micro or the macrofloc fractions during the three high discharge events, but this size class was consistently important during all events (Figure 2.5). Particle diameter data suggest that particles mainly increased in size in event 3, but coarser particles were also observed in events 1 and 2 (Figure 2.5). Particle diameter D_{10} was nearly constant through all events, demonstrating that finer particles are not well represented in such distributions.

Varying shear stress can influence EPSDs by altering flocculation or particle breakage, or by promoting SPM resuspension or deposition (Lee et al., 2012; Petticrew, 2005). Field and laboratory studies have observed that increases in shear stress can increase particle interaction, thereby stimulating the occurrence of flocculation and the development of coarser flocs through shear-dependent flocculation (Lee et al., 2012; Mikkelsen et al., 2006; Stone and Krishnappan, 2003). Flocculation occurring at higher shear stress was observed across the three study events. Increasing shear promoted the aggregation of the flocculi class into microflocs in event 1 at sites 1 and 3 between May 25th and 31st. Increasing shear stress also led to the flocculation of microflocs into macroflocs during event 1 at site 5 (May 23rd) (Figure 2.5). Shear-dependent flocculation was also observed in event 2 (site 3 – July 6th) and event 3 (site 7 – July 23rd), when increasing shear resulted in the flocculation of microflocs into macroflocs (Figure 2.5). Further, flocculation was also observed in periods when shear stress was relatively lower, such as in event 1 (site 1 – June 11th, and site 7 – May 22nd), in event 2 (all sites – July 3rd), and event 3 (site 1 – July 26th, site 3 and site 5 – July 19th and July 30th) (Figure 2.5).

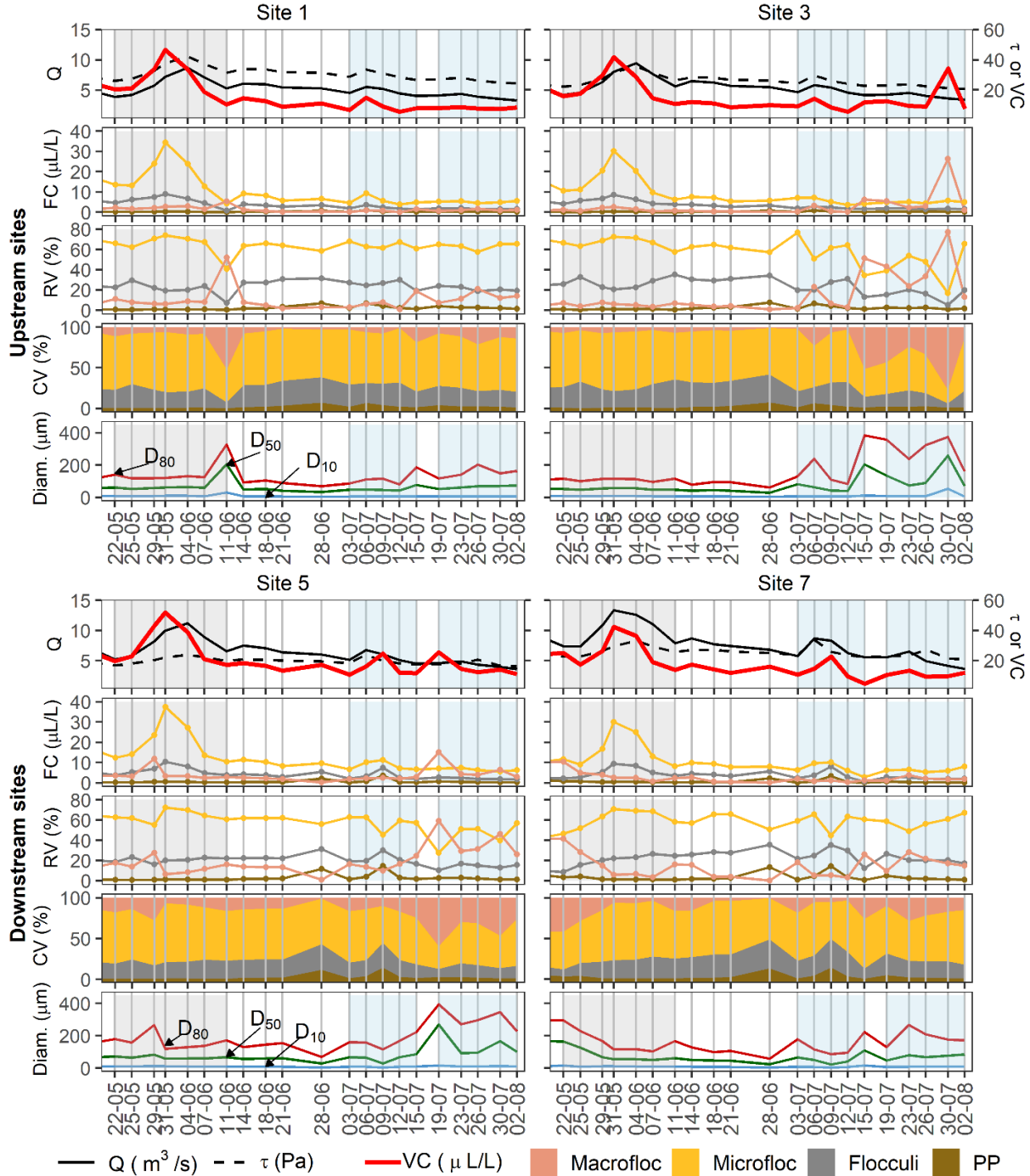


Figure 2.5. Temporal variation of measured discharge (Q), modelled bed shear stress (τ) and suspended sediment volumetric concentration (VC); floc absolute concentration (FC) of individual size classes; relative volume (RV) of size fractions; cumulative volumes (CV) of size fractions (where primary particles (PP) is the RV of PP , Flocculi equals the RV of PP + Flocculi, and so on; particle diameters D_{10} , D_{50} and D_{80} . Grey shaded areas correspond to Event 1, and blue shaded areas correspond to Events 2 and 3.

Bed shear stress has a dual effect in the process of flocculation. While increasing shear stress can promote particle interactions and benefit flocculation, high shear stress can lead to interactions that are too strong for the floc structure, resulting in floc breakage (Petticrew, 2005; Stone and Krishnappan, 2003). Floc breakage results in decreased relative volumes of coarser flocs and increased relative volumes of smaller flocs (Lee et al., 2012). Floc breakage was consistently observed across all events. In event 1, breakage of macroflocs into microflocs were observed at site 5 (May 31st), and at site 7 (May 25th – May 31st). In event 2, breakage of macroflocs into microflocs was observed at site 7 (July 6th) (Figure 2.5). In event 3, floc breakage from macroflocs into microflocs occurred when shear stress peaked at sites 3 and 5 (July 23rd), and at site 7 (July 23rd forwards) (Figure 2.5).

Decreasing volumes of coarser particles aligned with increasing volumes of finer particles were also observed under low shear stress conditions. This relationship was observed between the RV of microfloc and flocculi at event 1 at site 3 (June 11th) and between the RV of macrofloc and microfloc at the end of event 3 at sites 3 and 5 (August 2nd) (Figure 2.5). While particle deposition could have resulted in such observations (Mikkelsen et al., 2006), deposition requires bed shear stress to become lower than the SPM critical shear stress for deposition. However, previous studies have shown that this condition hardly ever occurs in the Crowsnest River (Stone et al., 2021b, 2011), especially under high-discharge conditions, which is the case of our study. SPM ingress in the gravel bed could still have occurred (Glasbergen et al., 2015), and flume experiments have shown that ingress can be size-selective, thereby affecting the EPSD of SPM (Koiter et al., 2015). However, more studies are required to better understand the role of ingress on EPSDs of SPM and on the multimodality of these size distributions. Therefore, the observed decrease in particle size under lower shear stress conditions suggests the breakage of more loosely-bound coarser particles.

While increasing shear might promote particle interaction and increase floc size, it is possible that once shear stress declines, flocs might decrease in size as well due to the lack of hydraulic forces promoting their size maintenance.

Changes in EPSDs can also result from the resuspension of previously deposited particles, and from particle mobilization from hillslopes and channel banks (Lee et al., 2012; Walling et al., 2000). Although high shear stresses can resuspend deposited sediment and lead to increases in the concentration of SPM (Mikkelsen et al., 2006), particle resuspension often increases the relative volumes of coarser particles in suspension (Lee et al., 2012). In this study however, such episodes were observed through relative and cumulative peaks in finer particle sizes. These peaks were observed on July 6th (sites 1 and 3), on July 9th (sites 5 and 7), and on June 28th (at all sites, but in a period outside the range of our assessed events) (Figure 2.5). Further, the lower range of discharges registered in 2019 (exceedance probability of 90%), suggest that particle resuspension was likely very minimal within the studied period. While particle breakage could have resulted in such peaks, the breakage of flocs into primary particles seldom occurs naturally (Ho et al., 2022). Thereby, because these observations all occurred following a series of rainfall events (Figure 2.2A), the data suggest that finer materials are likely being mobilized from channel bank or hillslope erosion. However, because the Crowsnest River has observably a well-armored channel bed and highly vegetated river banks (Stone et al., 2014), such contributions of finer particles to SPM are likely derived from upper areas in the study catchment. This hypothesis is consistent with observations reported by other studies conducted in the study area that show the potential of hillslope SPM mobilization in previously burned sub-catchments of the Crowsnest River is high (Silins et al., 2009) and that SPM from upper disturbed catchments can be transported in suspension even during low flow to the mouth of the Crowsnest River Basin (Stone et al., 2014).

2.5.2. Downstream variability of VC and EPSD

Study sites were grouped as “upstream” and “downstream” according to the degree of landscape disturbance to assess downstream variability in the VC and EPSD of SPM in the Crowsnest River. Upstream sites (S1 and S3) have land disturbance pressures that include industrial land clearing (such as mining), forest harvesting, urban, land clearing, and linear features (roads and ATV trails). Downstream sites (S5 and S7), in relation to upstream sites, have added natural and anthropogenic disturbances consisting of larger urban footprint, harvesting activities and wildfire (Watt et al., 2021). The median VC of SPM during all events was higher in downstream reaches compared to upstream reaches (Figure 2.6). This is in agreement with previous work conducted on catchments that are tributaries to our downstream sites, which observed increased delivery of fine particulate matter from hillslope to stream networks due the intense wildfire and salvage logging activities that occurred on those catchments (Silins et al., 2009; Stone et al., 2011). The downstream increase in VC highlights the increasing downstream effects of cumulative landscape disturbances in the Crowsnest River.

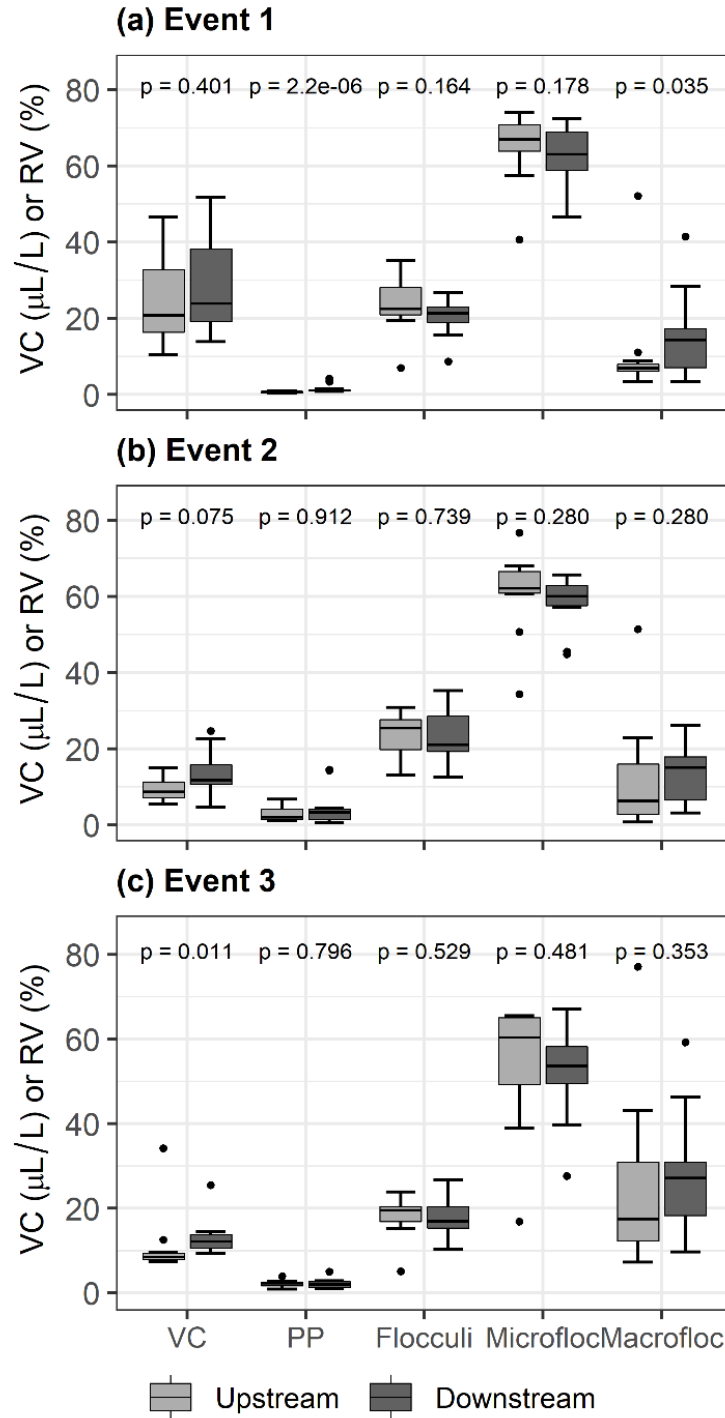


Figure 2.6. Comparison of upstream (S1 and S3) and downstream (S5 and S7) suspended sediment volume concentration (VC) and relative volume (RV) of each floc size classes using Wilcoxon rank sum test. Median, upper and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range. Event 1 (n=14 per reach), Event 2 (n=10 per reach), Event 3 (n=10 per reach).

Median values of the primary particle size class downstream were higher than upstream for events 1 (about 1.56 times) and 2 (about 1.62 times), but not for event 3 (about 0.87 times) (Figure 2.6). These differences, however, were small, and the primary particle size class was only significantly different between upstream and downstream sites during event 1 ($p < 0.0001$) (Figure 2.6). Median values of the flocculi fraction were consistently smaller downstream, and although no significant differences were observed between upstream and downstream reaches, the relative volume of this size class averaged over the three events was 1.1 times higher upstream than downstream. Even though no statistically significant differences were observed, median values of the microfloc size class over the three events were slightly higher (1.1 times) at the upstream reaches. Median values of the macrofloc fraction, on the other hand, were demonstrably higher downstream compared to upstream reaches in event 1, but less so in the other two events. The median relative volume of macroflocs over the three events was 2.1 times higher downstream than upstream.

Previous studies assessing the absolute particle size characteristics of fluvial SPM highlight that particle size selectivity can occur within channel networks. These studies attributed the increased presence of finer sediment in downstream reaches to the preferential deposition of coarser particles (Stone and Walling, 1997; Walling et al., 2000). While size selectivity and preferential deposition could explain the higher occurrence of the primary particle fraction observed in the downstream reaches of the Crowsnest River, it does not explain the higher volume of macroflocs observed in the lower reach. Therefore, the downstream variations in size classes are more likely to be explained by flocculation processes. In the present study, higher relative volumes of the macrofloc class and lower relative volumes of the flocculi and microfloc classes

were measured downstream compared to the upstream sites. Similar observations showing higher occurrence of macroflocs in downstream reaches have been reported elsewhere (de Boer et al., 2000; Gibbs et al., 1989; Stone et al., 2021b).

2.5.3. Inter-event variability of VC and EPSD

Inter-event variability of VC and EPSD are presented in Figure 2.7. Discharge measurements from the three events were all significantly different ($p < 0.05$) and bed shear stress was only significantly different between event 3 and the previous two events ($p < 0.005$). Measured discharge and modeled bed shear stress were consistently higher during snowmelt (event 1) but decreased progressively during storm events 2 and 3 (Figure 2.5). The highest VC values and specific sediment yield occurred during event 1 (Table 2.1). While the SPM VC between events 2 and 3 was not significantly different, specific sediment yield in event 3 was consistently smaller than event 2 (Table 2.1; Figure 2.7). These results demonstrate the importance of the snowmelt on the mobilization of higher amounts of SPM in the Crowsnest River, even during drier years (as discussed above).

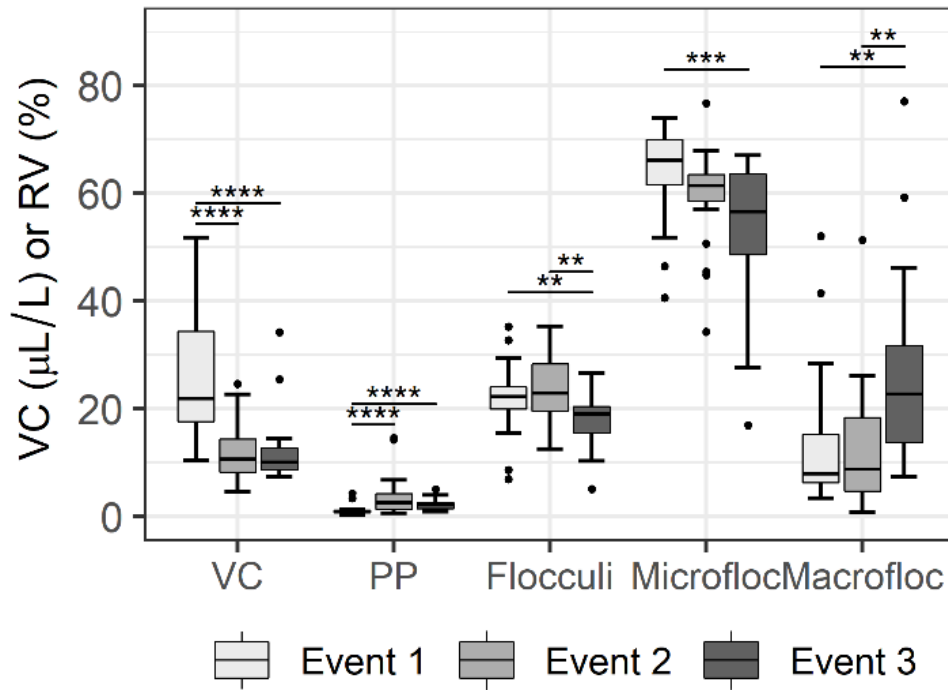


Figure 2.7. Inter-event comparison of suspended sediment volume concentration (VC) and effective particle size distribution (EPSD) using the Kruskal-Wallis test followed by a post hoc assessment with Dunn's test. Benjamini-Hochberg adjustments were made to p-values. Median, upper and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range. Event 1 (n = 28), Event 2 (n = 20), Event 3 (n = 20). Adjusted p-values: * p<0.05, **p<0.01, ***p<0.001, and ****p<0.0001.

Event 1 had a considerably lower volume of primary particles in suspension, indicating that this size class is more likely to be transported during rain events (Figure 2.7). The two observed peaks in the primary particle size class on June 28th and July 9th (as discussed above) are believed to have occurred due to either hillslope, or tributary channel bed/bank erosion rather than from the breakage of flocculated particles. Significant differences between events in the size classes of flocculi, microfloc and macrofloc demonstrate the differences in the flocculation dynamics in the study period. While volumes of the flocculi fraction in events 1 and 2 were significantly higher

than in event 3, volumes of the macrofloc class during the first two events were significantly lower than during event 3. The microfloc fraction during event 1 was significantly higher than for event 3 (Figure 2.7). These comparisons suggest that flocculation during event 1 was likely limited to the microfloc size class since high bed shear stresses developed in this event limited the formation of macroflocs. In contrast, smaller volumes of flocculi and microflocs, and higher volumes of macroflocs were observed during event 3. Even though the VC during event 3 was lower than the previous events, floc size increased significantly (Figure 2.7) due to lower bed shear stresses ($p < 0.005$) that developed during the last event. During event 2, which had comparable bed shear stress to event 1 ($p > 0.05$), but comparable VC of SPM to event 3 (Figure 2.7), flocculation was limited to the size ranges of flocculi and microfloc fractions.

2.5.4. Relationship between hydraulic properties and in situ particle size fractions

The relationship between hydraulic properties, VC, microfloc and macrofloc size classes at upstream and downstream reaches during three high discharge events are summarized in a PCA biplot (Figure 2.8). The first two components of the PCA explain a relatively high proportion (PC1 51.8% and PC2 27.2%) of variance in the data set. The data show that more upstream sites were correlated with the microfloc size class, while downstream sites were correlated with the macrofloc size class. Regarding the different events, event 1 was correlated with increased values of discharge, bed shear stress and VC, while events 2 and 3 were inversely correlated with these same variables. Discharge was positively correlated with increasing VC, but bed shear stress was better correlated to specific size classes. Bed shear stress was positively correlated to microflocs but negatively correlated to macroflocs. The PCA assessment shows that microfloc and macrofloc

volumes are inversely correlated, showing that the relative volume of the microfloc size class decreases as these particles flocculate into macroflocs.

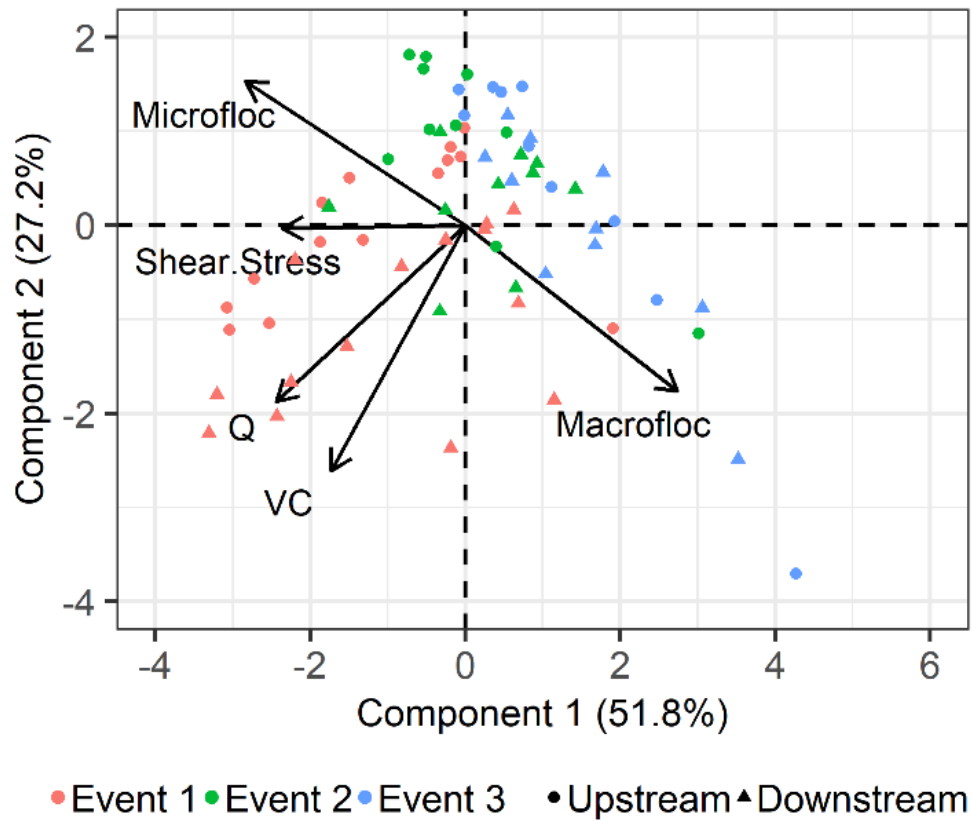


Figure 2.8. Principal component analysis (PCA) showing the first and second components, indicating relationships between hydraulic properties of suspended sediment volume concentration (VC), microfloc and macrofloc size classes at upstream and downstream reaches during the three studied events.

2.5.5. Implications for modelling the flocculation process in the Crowsnest River

A modelling framework for fine sediment transport including the flocculation process, has been proposed by Stone et al. (2021) to predict the downstream transport of sediment mobilized from burned and unburned areas of the upper basin of the Crowsnest River into the Oldman

Reservoir. The modelling framework includes a flocculation module, called RIVFLOC, developed by Krishnappan (1991). The RIVFLOC model uses a coagulation equation that incorporates terms that describe collision mechanisms resulting from Brownian motion, turbulent fluid shear, inertia of the sediment particles and differential settling. The cohesion that is responsible for the collided particles to bond together and form flocs was considered in terms of a cohesion-factor that was assumed to be constant through the whole spectrum of floc size distributions. The present study highlights the need to treat the cohesion factor as a variable and suggests using different values of the cohesion-factor for the different mechanisms of the formation of flocculi, micro and macroflocs to allow the model to predict the multimodal distributions better. The present study also provides support for refinement of the disaggregation scheme used in the RIVFLOC model wherein the break-up of flocs due to turbulent fluctuations of the flow field was formulated using a methodology proposed by Tambo & Watanabe (1979), and using the model parameters recommended by them. The present study allows for optimizing these parameters to model the disaggregation of the macro flocs into micro flocs in the Crowsnest River.

2.5.6. Study limitations

Field measurements in this study were taken at four different sites at an interval that ranged from 3 to 4 days. In agreement with our observations, previous studies assessing *in-situ* EPSD have reported more temporal than spatial variability in the EPSD of SPM (Phillips and Walling, 1999), and those using a high temporal resolution assessment have shown that EPSD can be highly variable in time (Williams et al., 2007). We did not explore the role of organic material in controlling the EPSD of the SPM in our study basin. We also did not quantify the benefits of refining the parameterization of cohesion or disaggregation within the RIVFLOC model using the

new understanding assembled by the work herein and the corresponding implications for river watershed management. Similar experimental work would be needed to support the application of RIVFLOC in other river watersheds and to understand the implications of any catchment-specific refinements to the cohesion or disaggregation parameters for model accuracy and landscape decision-making.

2.6. Conclusion

Time series of multimodal EPSDs were evaluated for three high discharge and turbulent shear events in a gravel-bed river in southern Alberta. The multimodal EPSDs which consisted of primary particles, flocculi, microflocs and macroflocs were dynamic under different conditions of turbulent shear. In agreement with the general theory of flocculation, the results of this study show that shear-dependent flocculation was the primary mechanism causing multimodal shifts in the EPSDs of SPM. At low turbulent shear stress, the EPSDs generally skewed towards a larger particle volume of micro and macro flocs suggesting an aggregate-dominant condition. However, under conditions of higher turbulent shear, EPSDs skewed toward smaller size fractions and a large volume fraction of floc building blocks were observed in a breakage-dominant condition. These observations have implications for advancing fine sediment transport models by a variable cohesion factor as a function of floc size class. Here, flocculation and particle breakage processes were assessed based on relationships between particle size and hydraulic properties. Further research is still required to better understand physical, chemical, and biological processes that govern flocculation. In addition, further investigation is still required to better understand the role of gravel-beds and ingress mechanisms on flocculation processes.

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Chapter 3. Challenges in measuring fine sediment ingress in gravel-bed rivers using retrievable sediment trap samplers

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3.1. Summary

The assessment of fine interstitial sediment accumulation in gravel-bed rivers is challenged by the lack of standardization and the debatable accuracy of assessments. In Chapter 3, >250 sediment traps were deployed to assess vertical and horizontal mechanisms of interstitial accumulation of cohesive and non-cohesive fine sediment (<2 mm). Three sediment trap designs (each design measuring different directional mechanisms of accumulation) were deployed in triplicates over seven deployment cycles at four sites in the Crowsnest River. The results demonstrated that, although ingress variability was higher in coarser (0.5 – 2 mm) non-cohesive particles relative to flocs (<500 μm), most ingress measurements presented high variability, which is likely due to natural variability but likely amplified due to the artificial conditions imposed by retrievable samplers. Further, it was observed that the assessment of directional ingress mechanisms through commonly used paired deployments led to the overestimation of either vertical or horizontal mechanisms. Better estimations were found when accounting for the proportional volume of samplers relative to the accumulation mechanisms being assessed through each trap design.

3.2. Introduction

Fine sediment (<2 mm) stored within the interstices of gravel-bed rivers is an important component of catchment fine sediment budgets (Foster et al., 2011). It naturally promotes matrix development (Frostick et al., 1984) and it plays an important role in nutrient cycling and aquatic health (Hauer et al., 2016; Wilkes et al., 2019). However, anthropogenic and natural landscape disturbances (e.g., harvesting, wildfires, droughts, and resource extraction) have increased fine sediment delivery to river systems (Naden et al., 2016; Owens et al., 2005; Walling and Fang, 2003). The subsequent deposition and storage (short- and long-term) of fine sediment within gravel-bed interstices can reduce substrate permeability and conductivity (Brunke, 1999; Schälchli, 1992; Wharton et al., 2017), decrease dissolved oxygen availability (Greig et al., 2005), and degrade benthic habitats used by aquatic organisms for key life stages (Jones et al., 2012a; Mathers et al., 2019). Landscape modifications have altered fine sediment deposition and accumulation dynamics, leading to legacy impacts in gravel-bed rivers (Emelko et al., 2016; James, 2013; Stone et al., 2021b; Watt et al., 2021), and an improved understanding of the strengths and limitations of assessment methods is required to ensure reliable evidence is generated in support of improved fine sediment management.

In high-energy gravel-bed rivers, fine sediment is known to have a complex interaction with the coarse channel bed framework (Legout et al., 2018). In these river systems, pressure gradients (leading to advective transport) and turbulent mixing (leading to turbulent diffusion) resulting from interactions between the flow and channel roughness elements can induce pore water flow and mass fluxes between the water column and the porous bed (Packman et al., 2004; Reidenbach et al., 2010). These interactions enable fine sediment to infiltrate the gravel interstices under bed shear stresses much higher than the critical shear stress required for fine sediment gravitational

deposition (Casas-Mulet et al., 2017; Glasbergen et al., 2015; Krishnappan and Engel, 2006) in a process denoted as fine sediment ingress, but also known elsewhere as entrapment (Krishnappan and Engel, 2006), infiltration (Frostick et al., 1984; Sear, 1993), intrusion (Beschta and Jackson, 1979), or depth filtration (Brunke, 1999). Ingress can occur vertically, through the downward infiltration of suspended particles (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018) or from finer fractions of the bedload (Frostick et al., 1984; Lisle, 1989), or laterally, through horizontal accumulation driven by pore water flow (Casas-Mulet et al., 2017; Harper et al., 2017; Mathers and Wood, 2016; Petticrew et al., 2007). Interstitial fine sediment can ingress until reaching an impermeable (deeper) layer in a process known as unimpeded static percolation (Gibson et al., 2009; Herrero and Berni, 2016). Alternatively, particles can get trapped at the upper gravel interstices, clogging the framework in a process known as ‘bridging’ or colmation. (Brunke, 1999; Evans and Wilcox, 2014; Lisle, 1989; Perret et al., 2018; Schälchli, 1992; Wooster et al., 2008). Collectively, these processes make gravel-bed rivers important for the transient storage of fine sediment (Mondon et al., 2021; Owens et al., 2005). Yet, field studies of fine sediment ingress *in-situ* are still relatively limited, and the methodologies currently available lack standardization to allow direct and easy comparison of field study results.

Several methodologies are used to assess fine sediment ingress in field and laboratory assessments. Within the laboratory setting, flume experiments with gravel beds can indirectly assess fine sediment ingress by comparing initial and final suspended sediment concentrations at each flume run (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018). Alternatively, flume experiments can also directly measure fine sediment ingress by deploying sediment traps (Carling, 1984). In the field, fine sediment accumulation (channel bed storage) has been assessed through resuspension techniques (Duerdoth et al., 2015; Lambert and

Walling, 1988), bulk sampling (McNeil and Ahnell, 1964), and freeze coring (Evans and Wilcox, 2014; Lisle, 1989; Petts, 1988). However, such techniques represent instantaneous snapshots of fine sediment accumulation, failing to provide information on the directional (vertical/horizontal) ingress mechanisms.

Fine sediment ingress rates and mechanisms have been commonly assessed with sediment traps (see Harper et al., 2017). Sediment traps consist of baskets that are filled with local washed framework gravel (removal of <2 mm sediment), and subsequently inserted within the gravel substrate. A range of ingress trap designs have been deployed in the literature. Lidless impermeable-walled ingress traps (herein denoted as vertical – V traps), which only allow infiltration through the open surface area, have been used to assess the vertical accumulation of fine sediment through either deposition or ingress (Frostick et al., 1984; Wood and Armitage, 1999). Adaptations of these V traps with added open bottoms have also been used to allow and quantify vertical exfiltration of fine sediment (Mathers and Wood, 2016). Lidded permeable-walled ingress traps (herein denoted as horizontal – H traps), which only allow infiltration through the lateral openings but not through the surface, have been used to assess horizontal ingress (Carling, 1984; Casas-Mulet et al., 2017; Petticrew et al., 2007). Lidless permeable-walled traps (herein denoted as horizontal-vertical – HV traps) have been deployed to measure fine sediment accumulation through vertical and horizontal mechanisms simultaneously (Casas-Mulet et al., 2017; Greig et al., 2005; Mathers and Wood, 2016; Petticrew et al., 2007). Paired deployment of sediment traps has been conducted to calculate vertical and horizontal ingress mechanisms. In paired assessments, HV traps are deployed paired with either V (Harper et al., 2017; Mathers and Wood, 2016) or H traps (Casas-Mulet et al., 2017; Petticrew et al., 2007), and differences in fine sediment accumulation between the two trap designs are used to estimate ingress directional

mechanisms. Although different sediment trap designs allow the quantification of ingress mechanisms, the accuracy of paired assessments is debatable and has been identified as an important research gap requiring further investigation (Harper et al., 2017). Here, we deployed three trap designs (horizontal-vertical - HV, horizontal - H, and vertical - V) in triplicate to: a) investigate variability in fine sediment ingress measurements within traps of the same design; b) evaluate the effects of trap design on the accumulation of fine sediment according to particle size and at a range of flow conditions, and; c) critically discuss the challenges of using different trap designs to measure vertical and horizontal sediment ingress mechanisms.

3.3. Methods

3.3.1. Study area

The Crowsnest River, one of three main tributaries of the Oldman Watershed, is a gravel-bed river located on the eastern slopes of the Rocky Mountains in southwestern Alberta, Canada (Figure 3.1A). Bed elevation over the ~10 km study reach changed from 1314 to 1260 m.a.s.l., and the average bed slope was 0.0041 m m^{-1} . The median bed particle size (D_{50}) was 24, 41, 82 and 70 mm at sites one to four, respectively. Baseflow is dominated by groundwater inputs from alluvial aquifers in the river valley (Waterline, 2013). Streamflow is strongly controlled by late spring and early summer snowmelt, while peak flows occur due to rain-on-snow or summer storms (Stone et al., 2014; Waterline, 2013). Concentrations of total suspended solids (TSS) in the Crowsnest River are typically low ($<5 \text{ mg L}^{-1}$), and elevated TSS is commonly associated with higher discharge events and sediment loads from tributary inflows (Silins et al., 2009). Further study site descriptions can be found in Silins et al. (2014) and Watt et al. (2021).

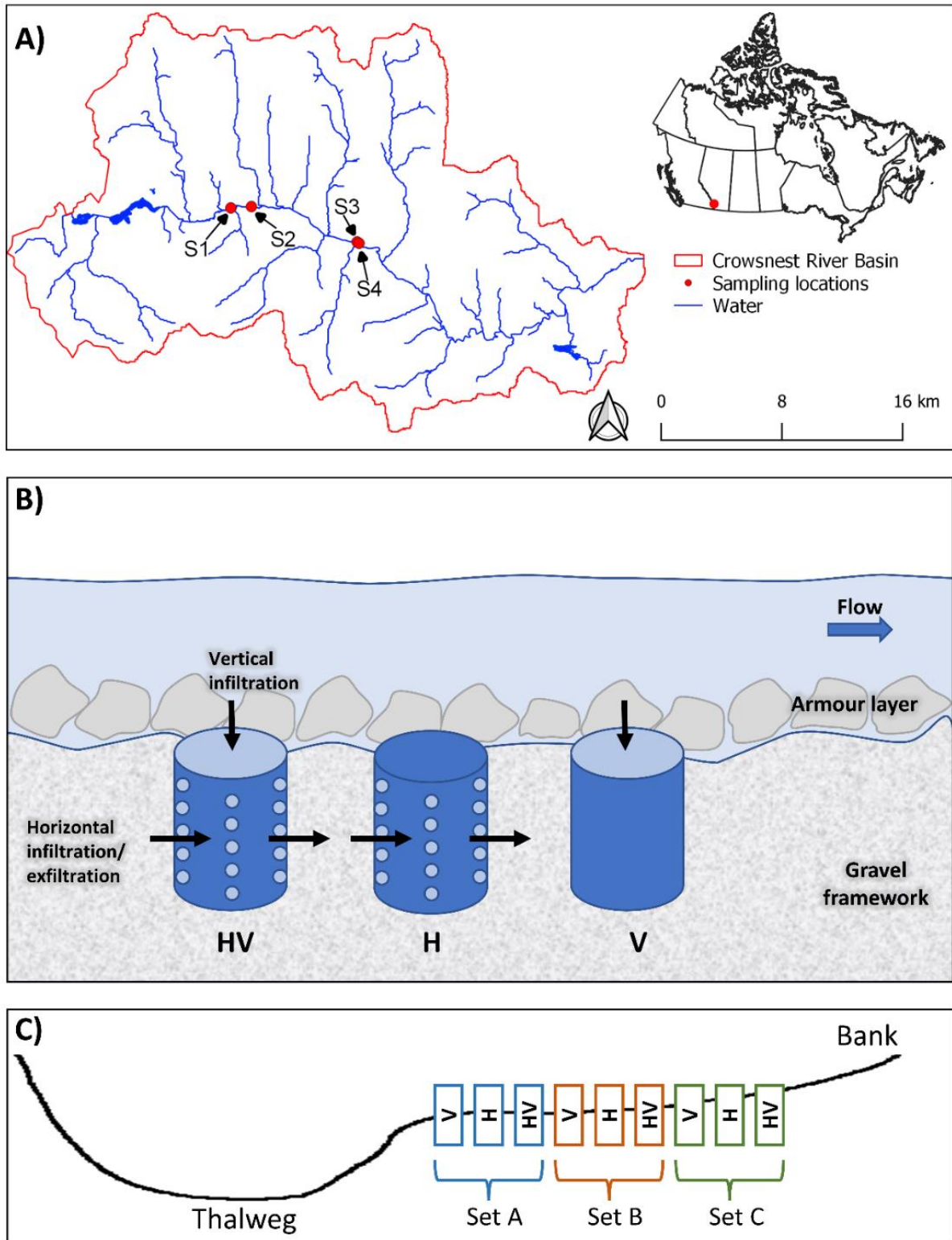


Figure 3.1. Location map (A), retrievable ingress trap designs and conceptualization of the ingress mechanisms being assessed by each trap type (B), and a schematic of the triplicate deployment *in-situ* (C).

3.3.2. Experimental design

Three designs of ingress traps were deployed in this study: HV, H, and V traps. All traps were constructed using 32 oz deli containers (surface diameter of 11.43 cm and height of 13.97 cm). The container walls pertaining to HV and H trap designs were perforated with 1 cm diameter holes (20 holes per trap) (Figure 3.1B). For HV and H traps, similarly to the samplers deployed by Casas-Mulet et al. (2017), each trap consisted of two tightly aligned containers, allowing for holes to be open during sampling, and closed during trap retrieval, preventing loss of accumulated fine sediment. Further, to prevent sediment loss upon retrieval, V and HV traps were also lidded before trap removal from the channel. Visually, minimal amounts of fine sediment were observed to leak out of traps during retrieval, and we believe this would not have affected our results. Traps were deployed in triplicates (Figure 3.1C) in four submerged gravel bars along the Crowsnest River during seven cycles of deployment (3 trap types x triplicates x 4 sites x 7 cycles = 252 traps in total; Figure 3.2). Sediment traps were deployed side by side, aligned and laterally centered in the gravel bars to avoid being too close to the thalweg or the bank. Further, trap designs were intercalated to avoid biases in accumulation as a function of their location within the gravel bar (Figure 3.1). The lengths of cycles were 4, 5, 10, and 6 days, for cycles 1 to 4, respectively, and 2 days for cycles 5 to 7 (Figure 3.3). Each trap was filled with representative framework gravel from each study site (sieve-washed with a 2 mm mesh) and manually shaken to promote a closer-to-natural gravel packing structure. Further, during trap preparation before deployment, care was taken to ensure that no gravels were “clogging” any perforated holes. Six out of the 252 traps were removed from the assessments (traps were found displaced, likely due to vandalism, given the high recreational usage of the study river), leaving a total of 246 traps. For the consistency of pairwise

comparisons, the pairs of the damaged traps were also removed (for example, if Cycle 2, Site 2, H-C was damaged, we also removed Cycle 2, Site 2, HV-C and V-C) (See Appendix B).

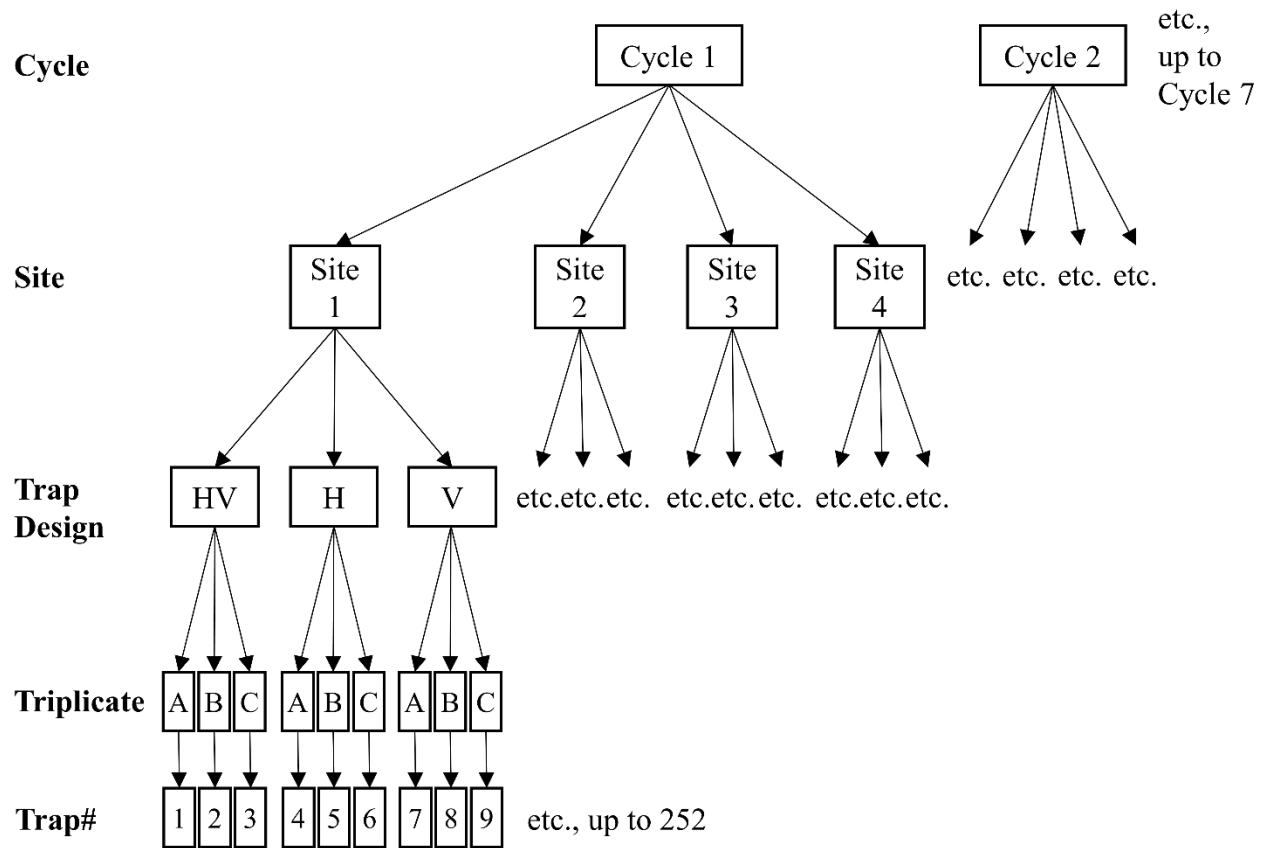


Figure 3.2. Schematic of the sampling design.

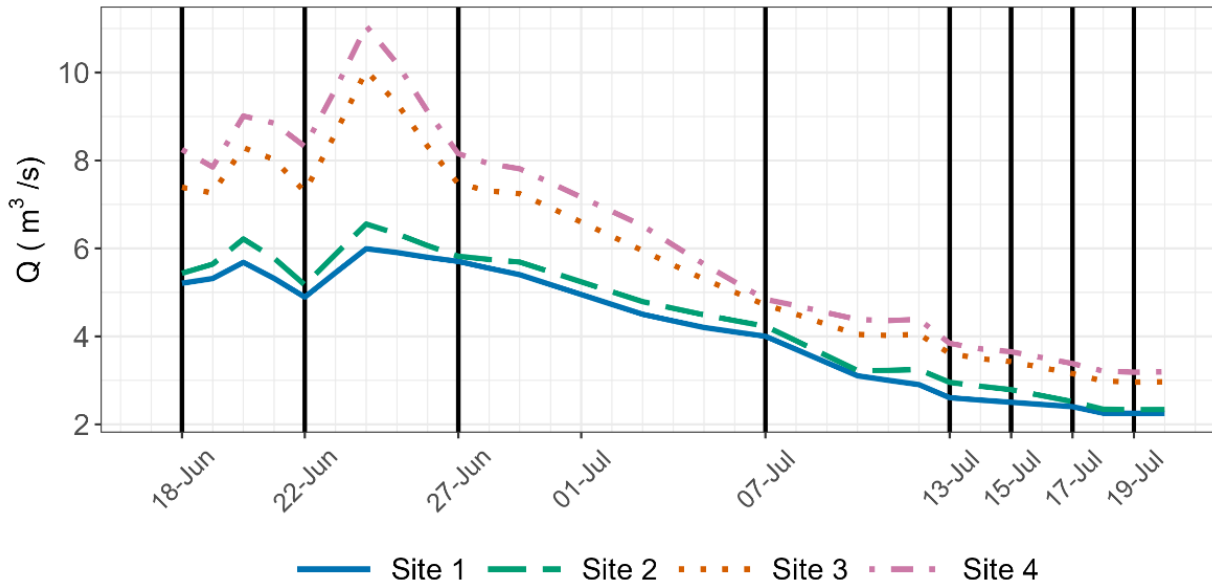


Figure 3.3. Measured discharge at the study sites. Vertical lines indicate the time delimitation of each deployment cycle.

3.3.3. Data assessment and statistical analyses

Fine sediment accumulated in each ingress trap (three replicates of each trap design) was wet sieved through 2 mm and 0.5 mm sieves, oven-dried and weighed, generating mass measurements for total accumulation <2 mm and for two size classes (<0.5 and 0.5-2 mm). Ingress rates were calculated in units of $\text{kg}\cdot\text{day}^{-1}$ to normalize accumulation according to the deployment period. Discharges (Figure 1.3) were measured with a FlowTracker2 (SonTek, Yellow Springs, OR, USA), and differences in flow condition were addressed by assessing the statistical effects of each deployment cycle (discussed below). Particle size distributions (effective and absolute) were obtained with a LISST-200x (Sequoia Scientific, Bellevue, WA, USA), which, through a laser diffraction principle, measures volume concentrations (VC) in 36 size bins for particles ranging from 1 to 500 μm . Particle size was measured from sediment-water samples collected while sieve-washing ingressed particles. Absolute particle size distributions (APSD) were measured after

dispersing the samples chemically, with sodium hexametaphosphate (5%), and mechanically, with ultrasonication (Naden et al., 2016; Phillips et al., 2000).

In order to obtain a mass estimation of ingressed fine sediment according to a range of size classes, while preserving flocculation of particles, effective particle size distributions (EPSD) were grouped into three size classes (< 67 , $67 - 130$, and $130 - 500 \mu\text{m}$), defined for comparison with similar studies (Harper et al., 2017; Mathers and Wood, 2016). The relative volume composition per size class in relation to the total VC measured at each sediment trap was calculated and used to estimate their weight composition by multiplying relative volumes with the measured mass of fine sediment $< 0.5 \text{ mm}$. The mass estimation of size classes $< 0.5 \text{ mm}$ was calculated based on the assumption that these particles are mostly flocculated. Here, comparisons between effective (flocculated) and dispersed particle size distributions have shown the flocculated nature of ingressed fine sediment $< 0.5 \text{ mm}$ (Figure 3.4), and, as such, their densities were estimated to approach the density of water (1 g cm^{-3}). This density value agrees with calculations between mass and volume concentration measured in our samples and was adopted for simplicity, as floc density has been observed to change with particle size (Glasbergen et al., 2015; Krishnappan, 2022; Krishnappan and Engel, 2006).

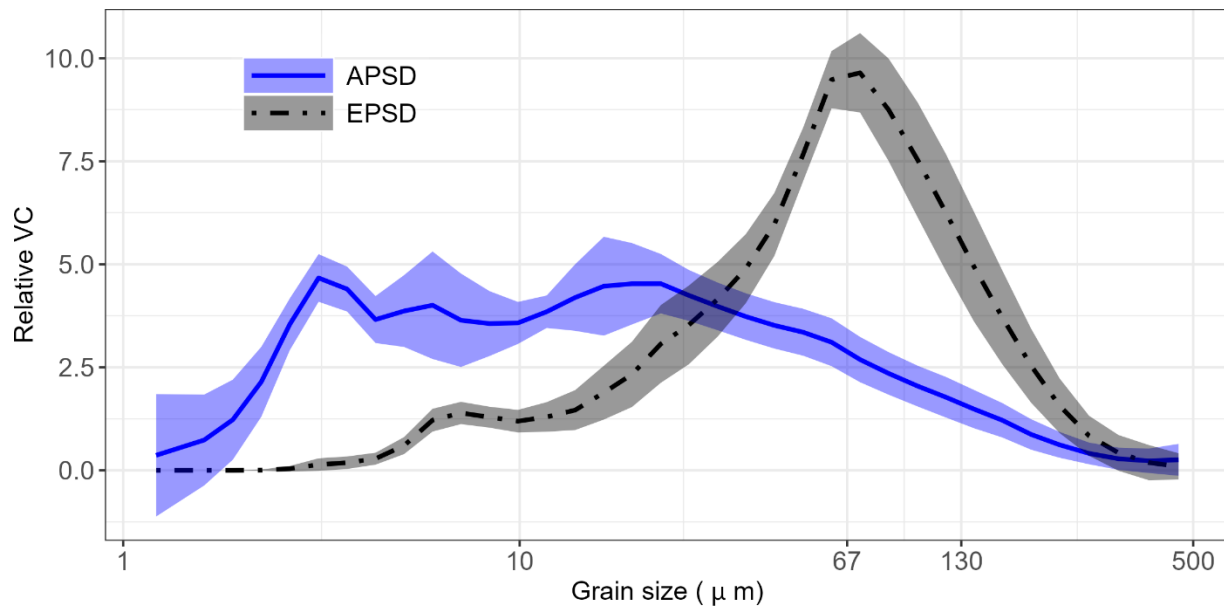


Figure 3.4. Absolute (APSD) and effective particle size distributions (EPSD) of ingressed fine sediment. Curves indicate median of all measurements ($n=246$) and shaded areas indicate corresponding ± 1 SD.

Descriptive statistics, including averages and relative standard deviation (coefficient of variation – CV), were calculated for the triplicate measurements conducted for each trap design. In this study, linear mixed effects models (LME) were used to assess the relationship between fixed factors (trap design, particle size, and deployment cycle) and ingress rates, by incorporating random factors (study sites) to account for data clustering and improve model fit compared to traditional linear models. The first LME model assessed the dataset pertaining to two size classes (< 0.5 and $0.5 - 2$ mm) of fine sediment ($n = 168$), while the following two models assessed size classes separately ($n = 84$ for each size class). For the LME models, ingress rates were log-transformed to improve normality, and values were standardized by centring data around means and scaling with respect to its standard deviation). Beta regression models were applied to evaluate the effects (and interaction effects) of trap design, particle size and deployment cycle on the

proportional content of particles within each size class ($< 67 \mu\text{m}$, $67 - 130 \mu\text{m}$, $130 - 500 \mu\text{m}$, and $0.5 - 2 \text{ mm}$). A preliminary assessment of size proportions using a binomial generalized LME, with sites fitted as a random variable, showed that different sites accounted only for little variation in the model, so the beta regression was used for simplicity. Pairwise comparisons were performed with a Wilcoxon signed rank test, using Benjamini-Hochberg correction for multiple comparisons.

To evaluate commonly used paired deployment methods to assess ingress directional mechanisms, we assessed the variability (mean and standard error) in our measurements and used linear regression models to relate direct assessments with estimates of ingress mechanisms. Here, we assumed that the comparison between H and V traps would directly assess solely horizontal and solely vertical measurements, respectively. In contrast, the comparison between HV and H would allow the direct measurement of horizontal mechanisms, while inferring (by their difference) vertical mechanisms, and the comparison between HV and V would allow the direct measurement of vertical mechanisms, while inferring horizontal mechanisms. Considering that all three traps had the same control volume, we investigated not only the 1:1 proportion between traps (i.e., comparing the mass accumulated in 1 V or 1 H with the mass accumulated in 1 HV) but also the 2:1 proportion (i.e., assuming that HV accumulated both mechanisms at the same time under the same control volume, its separated ingress mechanisms would have to be increased to be comparable with masses accumulated in either V or H; Hence, when applying the equation $V + H = a(HV)$ for each paired deployment, an average value of ~ 2 was found for the constant a).

All statistical analyses were performed using R Statistical Software (R Core Team, 2022) through the RStudio Integrated Development Environment (RStudio Team, 2022). LME models were fitted using the “lme4” package (Bates et al., 2015) with the restricted maximum likelihood estimation function. Conditional and marginal R^2 values from the LMEs were extracted using the

“MuMIn” package (Bartoń, 2023). Beta regression was fitted using the “betareg” package (Zeileis et al., 2021). The significance of predictors was determined using Anova (type 2 with Wald χ^2 statistics) with the “car” package (Fox et al., 2023). Pairwise comparisons were assessed with the “rstatix” package (Kassambara, 2021). All plots were created using the “ggplot2” (Wickham, 2016) and “ggpubr” (Kassambara, 2020) packages.

3.4. Results

Accumulation rates of fine sediment <2 mm, using the three designs of ingress traps deployed, are shown in Figure 3.5A. However, important differences in ingress rates were observed as a function of particle size through the LME models (Table 3.1 and Table 3.2). Results from the LME model assessing particles <0.5 and 0.5 – 2 mm showed that trap design alone did not significantly affect responses in ingress rates, but significant effects were observed regarding the interactions between trap design, particle size and deployment cycle (Table 3.1). The LME model assessing both <0.5 and 0.5 – 2 mm size classes, however, did not explain substantial model variance (marginal R^2 of 34.3%), with random factors improving the model by 17.5%, resulting in total model variance (conditional R^2) of 51.8% (Table 3.1). The LME results pertaining to each size class indicated that model fit improved as particle sizes decreased (conditional R^2) and that the clustering effect from sites became significantly more important as particle sizes increased (difference between conditional and marginal R^2) (Table 3.2). Except for particles 0.5 – 2 mm, the independent effect of trap design and its interaction with deployment cycle significantly affected responses in ingress rates for all size classes (Table 3.2). The beta regression model showed the significant effects between the interaction of trap type, particle size and deployment cycle on the proportional mass of accumulated fine sediment (Table 3.3).

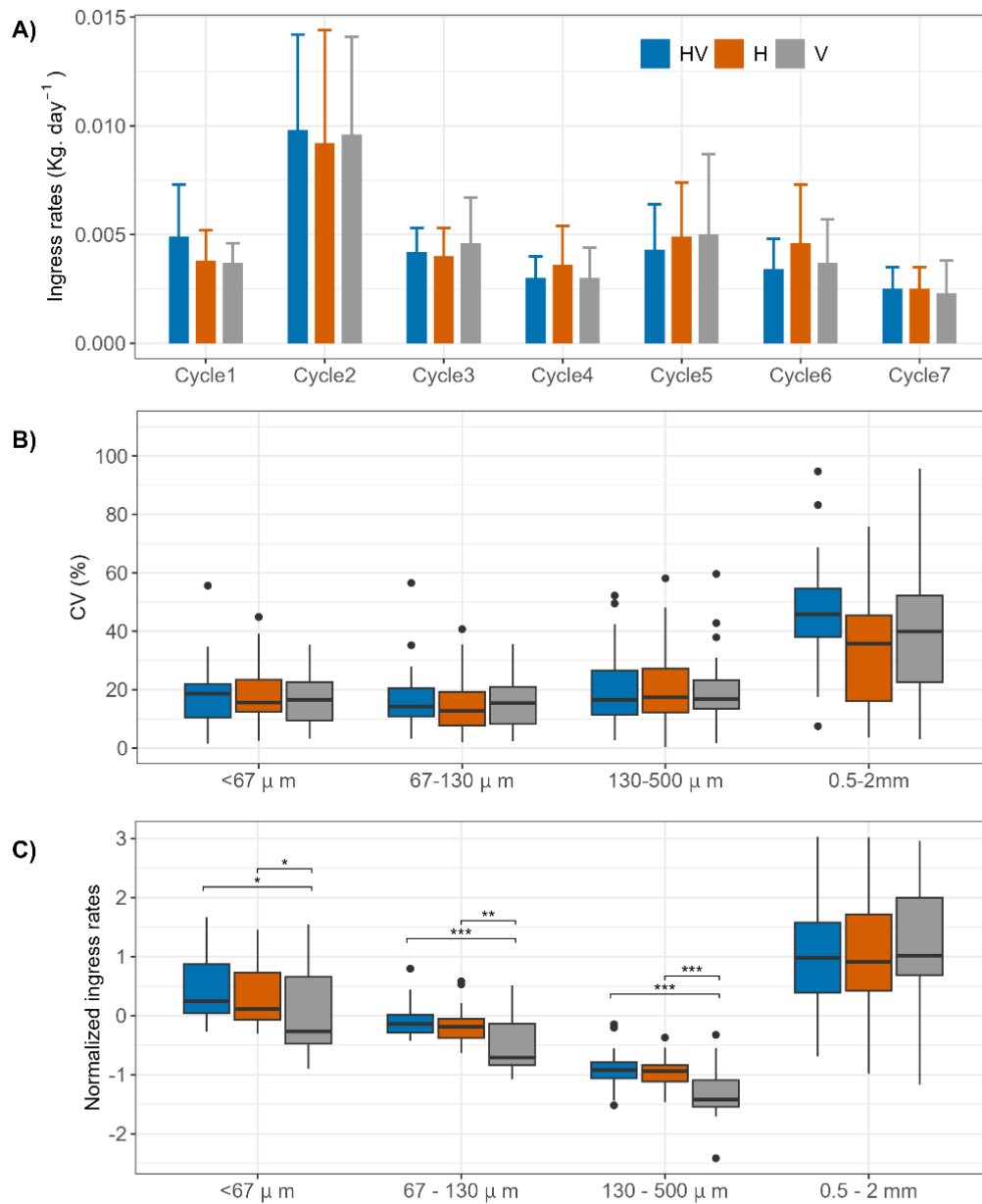


Figure 3.5. Mean (+1 SD) of fine sediment <2 mm accumulation rate ($n = 12$ for each ingress trap design) (A), coefficients of variation from the triplicate measurement of ingress rates (B), and Wilcoxon signed rank test pairwise comparison of ingress rates. In (B) and (C), $n = 28$ for each design of ingress trap. Adjusted (Benjamini-Hochberg) p -values: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and **** $p < 0.0001$. Median, upper, and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range.

Table 3.1: Summary of the LME model examining fine sediment ingress rates according to deployment cycle, trap design, and particle size class. Bold values represent significant results at the 95% confidence level.

Factor	df	<0.5 mm and 0.5 – 2 mm particle sizes (n = 168)	
		χ^2	p-value
Trap design	2	2.02	0.365
Trap design: Particle size	3	11.07	0.011
Trap design: Particle size: Deployment Cycle	18	105.69	<0.001
Marginal R ²		0.343	
Conditional R ²		0.518	

Table 3.2: Summary of the LME models examining fine sediment ingress rates according to deployment cycle and trap design, for particle size classes separately. Bold values represent significant results at the 95% confidence level.

Factor	df	<67 μ m (n = 84)		67 - 130 μ m (n = 84)		130 - 500 μ m (n = 84)		0.5 - 2 mm (n = 84)	
		χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
Trap design	2	58.32	<0.001	80.91	<0.001	45.69	<0.001	1.01	0.603
Trap design: Deployment Cycle	18	504.47	<0.001	208.34	<0.001	75.70	<0.001	81.85	<0.001
Marginal R ²		0.859		0.764		0.494		0.233	
Conditional R ²		0.873		0.781		0.662		0.767	

Table 3.3. Summary of the beta regression model examining the proportions of mass accumulation within each size class according to deployment cycle, trap design, and particle size class. Bold values represent significant results at the 95% confidence level.

Factor	df	Four size classes (n = 336)	
		χ^2	p-value
Trap design	2	0.003	0.999
Trap design: Particle size	3	692.76	<0.001
Trap design: Particle size: Deployment Cycle	18	141.25	<0.001
Pseudo R ²		0.764	

Variability in ingress rates, regarding the triplicate measurements, was generally high for all size classes (Figure 3.5B). Over 80% of all measurements presented CVs above 10%, and CVs were particularly higher for coarser particles. CVs were significantly higher for the 0.5 – 2 mm size class, compared to the smaller particles ($p < 0.001$), and for the 130 – 500 μm , compared to the 67 – 130 μm size class ($p < 0.05$) (see Appendix B). Variability between trap designs, however, was not significantly different for any size class (Figure 3.5B). Pairwise comparisons showed significant differences between sediment trap design for the < 0.5 mm size classes, but no differences were observed for 0.5 – 2 mm particles (Figure 3.5C). Linear regressions performed considering 1:1 and 2:1 proportions of fine sediment accumulation from H and V traps, showed that curves regarding 2:1 proportions were more similar to the measurements from HV traps, in terms of both intercept and slope (Figure 3.6). As such, the calculation of ingress mechanisms using 2:1 proportions resulted in more realistic estimations, when compared with direct assessments with H and V traps, and reduced the standard errors in both size classes (Figure 3.7). Furthermore, through the assessment on a 1:1 proportion, we observed that estimates between HV and V, and HV and H traps, overestimated vertical and horizontal mechanisms, respectively (Figure 3.7). When assessing ingress mechanisms using a 2:1 proportion, this bias was eliminated for estimations between HV and V, although it was only reduced between HV and H (Figure 3.7).

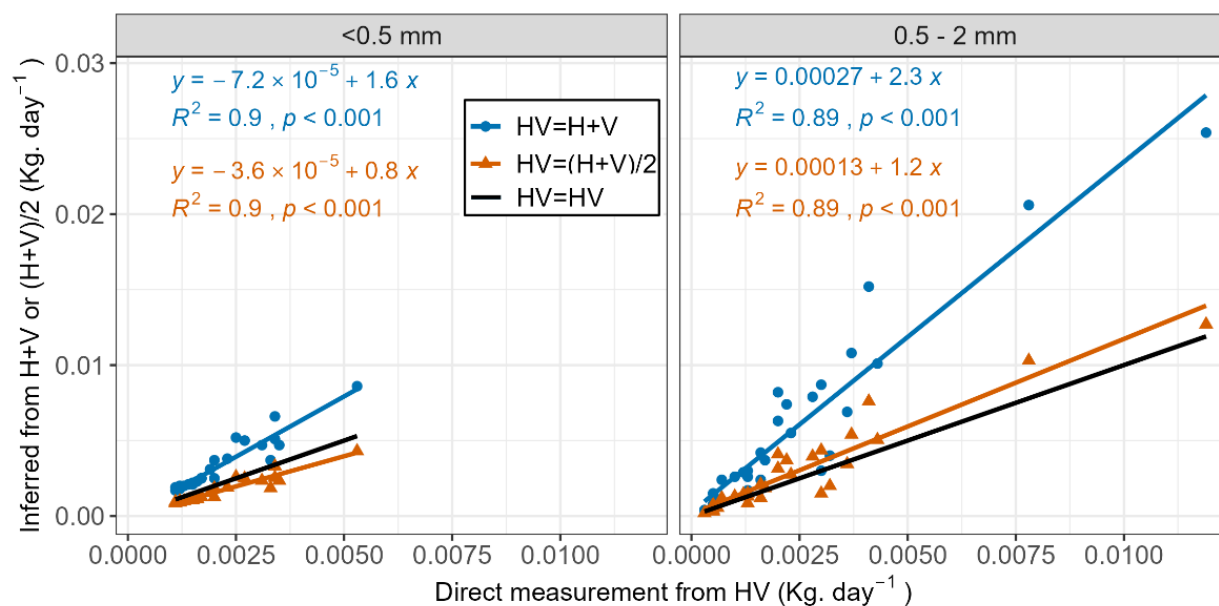


Figure 3.6. Linear regression between fine sediment ingress rates from HV traps against H + V traps (1:1 and 2:1 proportions). Black lines correspond to the curve $y = x$ (HV=HV). Points in the graph represent the mean taken from the triplicate measurements.

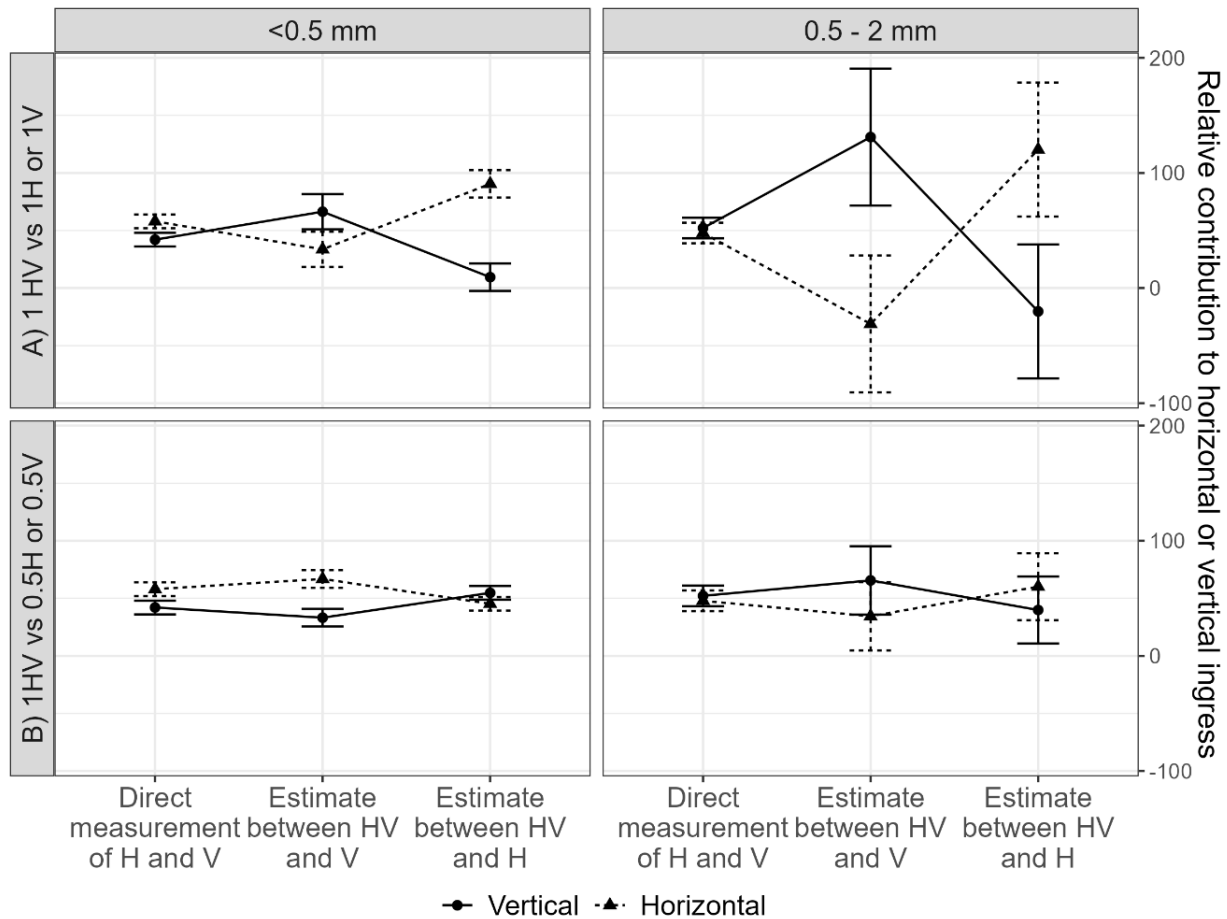


Figure 3.7. Assessment of ingress mechanisms (mean ± 1 SE). Paired estimates obtained by comparing fine sediment accumulation in: HV traps with accumulations in either H or V traps using a 1:1 proportion (A); and HV traps with either H or V traps using a 2:1 proportion (B).

3.5. Discussion

3.5.1. Measurement variability

This study sought to examine the variability of fine sediment ingress measurements taken using three designs of sediment traps. High measurement variability was observed across all trap designs, and it was particularly high for $0.5 - 2$ mm particle sizes, demonstrating the importance of size effects (discussed below) on fine sediment ingress measurements. To the authors' best

knowledge, triplicate measurements of ingress rates, like the ones performed here, have not been performed elsewhere. Similar studies deploying replicates of traps have also reported high variability within measurements (Casas-Mulet et al., 2017; Harper et al., 2017; Sear, 1993). However, those studies differ from ours in the sense that their replicates were deployed to assess fine sediment ingress variability between channels or within channel features, while our triplicates were deployed close to each other to assess variability within traps of the same design.

Previous flume studies assessing turbulent flow interactions with gravel-beds have shown that small-scale bed topography (such as protruding gravels) can increase turbulent mixing, leading to heterogeneous mass flux exchanges at the sediment-water interface (Reidenbach et al., 2010). As such, the observed high variability in ingress measurements can be partially attributed to the flow-sediment interactions in this gravel-bed river leading to naturally high measurement variability. However, it is also likely that the artificial gravel structure and altered bed roughness created during trap deployment (Casas-Mulet et al., 2017; Harper et al., 2017) have inflated natural variability. Since high variability was also observed in H traps, which were kept lidded, our observations demonstrate that even the slightest differences between gravel organization inside and around the traps were able to affect ingress measurements. The utilization of clean gravels (>2 mm) for the assessments is also an inherent methodological challenge of sediment traps, as it has been observed to replicate unnatural conditions of infiltration, with higher porosity increasing infiltration rates (Petticrew et al., 2007). Accordingly, the length of the deployment cycle can also affect the measured accumulations, given that shorter cycles will have the clean gravel effect inflated, while longer cycles might replicate a closer-to-natural framework setting (Harper et al., 2017). Long deployment periods, however, have been observed to increase interstitial clogging (Harper et al., 2017). Here, we did not observe any significant relationships between ingress

measurements and deployment length, and no gravel clogging was observed to develop within our study period. These observations highlight the intrinsic methodological challenges of assessing fine sediment ingress with sediment traps. Our results demonstrate that the deployment of replicates, which are not commonly observed in field assessments, can help improving measurement accuracy, especially regarding sand fractions.

3.5.2. The effects of trap design on fine sediment ingress

In this study, we sought to understand the differences between sediment trap designs according to particle size at a range of flow conditions. To the best of our knowledge, no other studies have investigated sediment ingress using three sediment trap designs (HV, H and V), and the only methodological evaluation of such samplers has been conducted by Harper et al. (2017). As observed in this study and demonstrated elsewhere (Casas-Mulet et al., 2017; Harper et al., 2017; Mathers and Wood, 2016; Petticrew et al., 2007), different trap designs might lead to significantly different ingress rate measurements. These differences in measurements can occur due to the predominance of either vertical or horizontal ingress mechanisms, but they can also occur due to the inherent nature of each design since natural flow pathways are altered differently according to trap design (Harper et al., 2017).

Here, differences between samplers regarding 0.5 – 2 mm particles were only significant when considering the effects of deployment cycle (Table 3.2, Figure 3.7), which we believe might be related to the high variability observed across samplers for this size class. On the other hand, for particles <0.5 mm, differences between trap designs were significant both independently and as a function of deployment cycle (Table 3.2, Figure 3.7). In accordance with our observations, Mathers and Wood (2016) found no significant differences between HV and V-like trap designs

regarding the accumulation of 1 – 2 mm particles, while the opposite was true for smaller particles. Conversely, Harper et al. (2017) observed significantly higher accumulation of particle sizes 0.125 – 2 mm in HV rather than in V-like traps, but no significant differences were observed for <0.125 mm particles. Although Harper et al. (2017) observed such size effects, they did not observe significant differences between traps according to the proportions of size class, indicating that differences were simply due to the higher mass accumulated in HV traps (a clogging or ‘bridging’ layer developed on their V traps, preventing further ingress). Here, in contrast with their observations, no clogging formed in our samplers, and significant differences between trap types regarding the proportions of size classes were observed (Table 3.3). The observed proportional differences found in our study indicate that trap type indeed influenced the size distributions of ingressed fine sediment.

Here, differences between traps were observed to change as a function of particle size and deployment cycle, reflecting the hydro-sedimentological regime of the sampling period. In this study, the discussion is focussed on the methodological perspective of observed differences, but further research is required to investigate the effects of hydro-sedimentological drivers on ingress rates and mechanisms.

3.5.3. Inferring sediment ingress mechanisms as a function of retrievable trap design

Several studies have relied on the paired deployment of different designs of sediment traps (HV paired with either H or V) to estimate vertical and horizontal contributions of fine sediment (Casas-Mulet et al., 2017; Harper et al., 2017; Mathers and Wood, 2016; Petticrew et al., 2007; Sear, 1993). However, in a methodological evaluation regarding paired deployments, Harper et al. (2017) inquired whether such assessments truly capture directional ingress mechanisms,

considering the artificial conditions imposed by ingress traps (altered gravel porosity and interstitial flow pathways according to each trap type). Therefore, this study sought to explore the comparisons between HV with either H or V sediment traps to investigate whether directional ingress mechanisms could be assessed through paired deployment.

Here, we observed higher errors in the estimation of ingress mechanisms when comparing accumulated fine sediment on a 1:1 proportion – especially for the 0.5 – 2 mm size fraction (Figure 3.7A). We also observed bias in the estimations of ingress mechanisms using the 1:1 proportion, in which paired deployments between HV and V, and HV and H overestimated vertical and horizontal ingress mechanisms, respectively (Figure 3.7A). This overestimation, which has also been observed by Casas-Mulet et al. (2017), occurs when HV traps accumulate less fine sediment than H or V traps, leading to estimations of horizontal or vertical mechanisms to be >100%. For instance, if H traps accumulated more than HV, we would infer that >100% of ingress would have occurred due to lateral movements, consequently leading to the inference of zero vertical ingress. However, out of 168 observations (averaged measurements from triplicate sampling), 41 registered higher accumulation in H or V, compared to HV traps. Our observations suggest that H or V traps are not accumulating more fine sediment because those mechanisms are predominant but because HV traps are more susceptible to fine sediment flush due to turbulent mixing since these traps have higher connectivity to both lateral and vertical flows (Casas-Mulet et al., 2017; Harper et al., 2017; Tonina and Buffington, 2009). Further, the 1:1 comparison of HV with either V or H traps might be misleading since HV traps measure two ingress mechanisms under the same control volume, whereas H or V traps measure only one. The errors in ingress mechanisms decreased for both size classes when performing assessments using a 2:1 proportion (Figure 3.7B). The 2:1 proportion

also eliminated the bias through paired deployments between HV and V, although it did not eliminate it in deployments between HV and H (Figure 3.7B).

3.5.4. Standardization of fine sediment ingress measurements and future assessment suggestions

In this study we observed a good agreement when comparing HV measurements with H + V (on a 2:1 proportion; Figure 3.6). However, because inferences between HV with either H or V can result in inevitable biases due the higher flow connectivity in HV traps, direct assessments through H and V traps led us to a better assessment of ingress directional mechanisms. We highlight that no clogging was observed in this study, and its occurrences could have compromised the assessment of directional mechanisms, as observed elsewhere (Harper et al., 2017). As such, in environments where fine sediment regimes might lead to clogging on V-like sediment traps, paired deployments between HV and H traps could be recommended instead. Therefore, the determination of what sediment traps to use in future assessments might rely on a general background understanding of the local fine sediment dynamics including evidence for ‘bridging’. Further, deploying all three types of traps might lead to more thorough investigations, considering the complexity of ingress processes.

Further, ingress rates have been commonly reported in terms of $\text{kg day}^{-1} \text{ m}^{-2}$, as such rates allow for temporal and spatial normalization when comparing fine sediment accumulation. However, other than traps like the V samplers used in this study, the accumulation area of other trap designs might not be limited to their top surface. Accordingly, defining a lateral accumulation area for trap designs such as HV and H, is challenging since the perforated openings on the lateral or the lee sides of the traps might also lead to fine sediment exfiltration. Consequently, ingress

comparisons between different studies should consider and regard the methodologies applied elsewhere since accumulation areas can affect normalized ingress rates.

3.6. Conclusions

There has been growing interest in the literature in improving knowledge on fine sediment ingress and its directional infiltration mechanisms. Reliable measurements, which depend on accurate methodologies, are needed to refine fine sediment transport models, which, in turn, are required to inform land use management practices. As such, measurement techniques need to be better understood to reproduce precise and comparable results. To the author's knowledge, this is the first study to measure the variability of ingress using sediment traps with differing designs. All trap designs presented high variability, which could be due to natural variability in ingressing particles, but it is likely being inflated due to the inevitably altered channel bed roughness when deploying samplers. Here, we observed important differences in sediment trap design according to particle size and deployment cycle, and future studies are required to investigate the hydro-sedimentological drivers of such differences in ingress processes. This study demonstrated that ingress mechanisms were well measured with H and V traps, but paired comparisons with HV generated less reliable results. Such paired comparisons might be further compromised in investigations where high ingress rates result in clogging of gravel interstices in V traps.

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Chapter 4. Hydro-sedimentological drivers of fine sediment ingress in a gravel-bed river

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4.1. Summary

Flocculation considerably alters the transport properties of particles by changing their effective size, density, and settling velocities, affecting fine sediment interaction with the gravel-bed (deposition and ingress), their fate, and retention time within channel interstices. In Chapter 4, the results of interstitial fine sediment accumulation according to particle sizes were evaluated against hydraulic and sedimentological changes in the flow field. Mean flow hydraulic parameters derived from the MOBED flow model and measured suspended sediment (mass and volume) concentrations were assessed to identify hydro-sedimentological drivers of interstitial accumulation according to particle size. The results demonstrated the distinct behavior between non-cohesive and flocculated particles, with most hydro-sedimentological drivers explaining the interstitial accumulation of flocculated sediment but not the accumulation of non-cohesive particles. Vertical ingress was higher during higher discharge events, but horizontal mechanisms prevailed during lower discharges. Modal similarities between suspended and ingressed particle size distributions suggest that both particle groups likely originate from the same catchment source (channel or non-channel). However, differences between volume concentrations between suspended and ingressed particles suggest that ingressed particles are either finding better opportunities to flocculate within the interstitial flow, or that coarser flocs found in suspension are preferentially ingressing relative to smaller flocs.

4.2. Introduction

Gravel-bed rivers draining mountainous, forested watersheds are critical sources of high-quality water (Emelko et al., 2016, 2011), and they play a crucial role in maintaining regional ecological integrity (Hauer et al., 2016). However, anthropogenic and climate change-exacerbated landscape disturbances have been increasing fine sediment delivery into these rivers (Goode et al., 2012; Owens et al., 2005). Fine sediments (<2 mm) comprise cohesive (<63 μm) and non-cohesive solids. In contrast to non-cohesive sediment, cohesive particles can flocculate with organic and inorganic solids within the flow field, forming flocs (Droppo and Ongley, 1992). Flocs present larger effective (flocculated) particle sizes and lower densities (Droppo, 2001) that alter their transport properties compared to their primary particles (Mehta and Partheniades, 1975). Accordingly, cohesive particles are an important vector for many pollutants and contaminants such as metals, phosphorus, and organic compounds (Allan, 1986; Ongley et al., 1992), and as such, understanding their transport and fate is critical for river and aquatic ecosystem health.

Fine sediment ingress – denoted elsewhere as entrapment (Krishnappan and Engel, 2006), infiltration (Frostick et al., 1984; Sear, 1993), intrusion (Beschta and Jackson, 1979), or depth filtration (Brunke, 1999) – is defined as the mechanism responsible for the accumulation of fine sediment within the porous spaces in gravel- or cobble-bed river channels. Under pre-disturbance conditions, interstitial fine sediment supports the development of the substrate matrix (Frostick et al., 1984), and it plays an important role in nutrient cycling and aquatic river health (Hauer et al., 2016; Wilkes et al., 2019). However, landscape disturbances can increase hillslope-channel connectivity, augmenting fine sediment delivery rates (Koiter et al., 2013; Owens et al., 2005) and channel deposits of fine sediment (Frostick et al., 1984). More specifically, excess interstitial cohesive sediment can lead to immediate and legacy post-disturbance impacts that affect the

chemical, physical, and biological aspects of aquatic health (Bilotta and Brazier, 2008; Kemp et al., 2011; Owens et al., 2005; Walling et al., 2003; Wilkes et al., 2019; Wood and Armitage, 1997). Despite the previously reported water quality and ecological impacts, the complex interactions between fine sediment and coarse-grained bed frameworks challenge the understanding of fine sediment ingress, and further investigations are required to advance knowledge on ingress drivers and mechanisms. Further, while knowledge advances have been made for cohesive sediment transport in riverine environments (Droppo and Krishnappan, 2016; Lamb et al., 2020; Legout et al., 2018; Livsey et al., 2022), very little is currently known about the ingress mechanisms of flocculated particles in gravel-bed rivers.

Gravel-bed rivers in mountainous landscapes are characterized by high-velocity turbulent flows in which bed shear stresses often exceed the critical shear stress required for fine sediment gravitational deposition (Droppo and Krishnappan, 2016). In these rivers, particle settling is often restricted to areas of low flow velocity due to flow separation, such as pools, bars, in the lee of vegetation, wood debris, boulders, and even protruding gravel or cobble grains (Legout et al., 2018; Rathburn and Wohl, 2003; Wood and Armitage, 1997). Once particles settle onto the streambed from gravitational deposition, ingress can occur, given sufficient pore space availability within the framework (Brunke, 1999). Further, fine sediment ingress can also occur due to advective transport and/or turbulent diffusion (Casas-Mulet et al., 2017). Further, in combination, ingress and exfiltration processes cause gravel-bed rivers to be important transient stores of fine sediment, with concomitant implications for legacy impacts and the timing of responses to landscape disturbance effects (Owens et al., 2005; Walling et al., 2003).

Advective transport occurs due to pressure gradients created by the interaction between flow and flow obstructions such as bedforms (Tonina and Buffington, 2009, 2007), or substrate

heterogeneity affecting subsurface hydraulic conductivity (Cardenas et al., 2004). Turbulent diffusion occurs when roughness elements, such as protruding grains, create a layer of heterogeneous shear stresses at the sediment-water interface (Reidenbach et al., 2010). This roughness effect can transfer turbulent momentum between stream and pore water flows, leading to non-zero velocities within the upper bed sediment layer (Packman et al., 2004; Reidenbach et al., 2010; Tonina and Buffington, 2009). Contrary to finer sand-bed alluvial streams, both advective transport and turbulent diffusion have been observed to influence coarse-grained channels even in the absence of bedforms, and the decoupling of the two processes is not possible due to the complexity of turbulent flows (Packman et al., 2004). Both advective and diffuse transport allow mass flux transfers between flow and the porous streambed, consequently allowing downwelling and upwelling fine sediment transport (Casas-Mulet et al., 2017; Mathers and Wood, 2016; Reidenbach et al., 2010). Porewater velocities produced by turbulent mixing near the sediment-water interface can further stimulate horizontal and lateral movement of fine sediment within the bed framework (Carling, 1984; Casas-Mulet et al., 2017; Petticrew et al., 2007). Due to the complex nature of fine sediment ingress, sediment transport models either disregard the ingress process entirely or limit its representation to the infiltration of sediments deposited onto the channel bed (gravitational deposition). However, fine sediment (cohesive and non-cohesive) ingress has been observed to occur under flow energies that are considerably higher than the critical conditions required for the gravitational deposition of fine sediment (Casas-Mulet et al., 2017; Droppo and Krishnappan, 2016; Glasbergen et al., 2015; Mooneyham and Strom, 2018).

Interstitial fine sediment can be sourced from the suspended load (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018) or from finer fractions of the bedload (Frostick et al., 1984; Lisle, 1989). After reaching the upper layer of the channel bed, either from

gravitational settling or from advective/diffusive transport, particles can move downwards until reaching an impermeable layer in a process known as bottom-up ingress or unimpeded static percolation (Gibson et al., 2009; Herrero and Berni, 2016). Ingressing particles, however, can clog channel interstices (Evans and Wilcox, 2014; Lisle, 1989; Perret et al., 2018; Schälchli, 1992; Wooster et al., 2008) in a process that has been denoted elsewhere as colmation (Brunke, 1999; Wharton et al., 2017), bridging (Gibson et al., 2009), or seal (Lisle, 1989). The occurrence of clogging depends on the size ratios between the framework and fine sediment grains (Gibson et al., 2009; Herrero and Berni, 2016), the ratio between sediment delivery and ingress rates (Beschta and Jackson, 1979; Wooster et al., 2008), and the quality (cohesiveness) of ingressing fine sediment (Shrivastava et al., 2020). Conversely, ingressed fine sediment can be exfiltrated from the channel interstices. Fine sediment exfiltration without channel framework mobilization or cutting is generally limited to the upper layers of the bed (Detert and Parker, 2010; Kuhnle et al., 2016; Schälchli, 1992). Exfiltration of ingressed particles from deeper within the channel framework can occur to some extent due to groundwater upwelling (Brunke, 1999), while bulk exfiltration occurs when stream capacity is sufficient to disrupt the armour layer and mobilize framework grains (Beschta and Jackson, 1979; Mooneyham and Strom, 2018; Schälchli, 1992). Fine sediment ingress and clogging are physical processes that can be affected and strengthened by chemical and biological controls. Here, we focused on the physical controls, but further information regarding biological and chemical controls can be found in a range of sources (e.g., Gerbersdorf et al., 2008; Grabowski et al., 2011; Wharton et al., 2017; Wilkes et al., 2019).

While previous studies have advanced knowledge of fine sediment (<2 mm) ingress mechanisms in gravel-bed rivers (e.g., Beschta and Jackson, 1979; Brunke, 1999; Tonina and Buffington, 2007; Wooster et al., 2008; Casas-Mulet et al., 2017), few studies have examined the

role of cohesive fine sediment in such interactions, and these have been predominantly performed in controlled laboratory settings using flumes (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018; Shrivastava et al., 2020). To the authors' best knowledge, no studies have reported on the effective (flocculated) size properties of ingressed cohesive particles and how hydro-sedimentological regimes drive the ingress of flocs. As such, improved knowledge of fine sediment ingress, especially regarding its cohesive fraction and the relationships between ingress directional mechanisms under different sediment supply and discharge conditions, is required to advance existing physical and contaminant transport models (Casas-Mulet et al., 2017; Evans and Wilcox, 2014; Wharton et al., 2017). *In-situ* investigations of sediment ingress are limited but are required to represent interactions between drivers and ingress dynamics more accurately. Accordingly, the objectives of this study were to: i) evaluate the role of flocculation on particle size properties of ingressed sediment; ii) investigate the relationship between hydro-sedimentological parameters and fine sediment ingress rates across a range of sediment supply and flow conditions; iii) evaluate the directional ingress mechanisms that are predominant in the Crowsnest River, and; iv) critically discuss the legacy impacts that can result from the observed ingress dynamics pertaining to the ingress of flocculated particles.

4.3. Methods

4.3.1. Study site

The Crowsnest River is located on the eastern slopes of the Canadian Rocky Mountains in southwestern Alberta (Figure 4.1). Its headwaters originate in upper montane snowmelt-dominated regions that drain into the Crowsnest Lake (1357 m.a.s.l.), further flowing eastward from the lake through the municipality of the Crowsnest Pass into the Oldman Reservoir (1113 m.a.s.l.).

Groundwater contribution from alluvial aquifers in the river valley regulates baseflow, while snowmelt and rain events control peak flow in the river (Stone et al., 2014; Waterline, 2013). Average annual precipitation ranges from ~400 to 1000 mm year⁻¹. The average bed slope over the ~10 km study reach is 0.0041 m m⁻¹ (Figure 4.1). The concentration of suspended solids (total suspended solids – TSS) in the Crowsnest River is normally <5 mg L⁻¹ during base flow but can exceed 100 mg L⁻¹ during snow melt and stormflow conditions (Maltauro et al., 2023; Silins et al., 2009). The study catchment is partially covered by crown land forests (subalpine and montane forests, and shrubland). Land use consists of industrial (predominantly underground mining and forestry activities), urban, and recreational, with anthropogenic pressures increasing in the downstream direction of the river (Watt et al., 2021). The tributary catchment upstream of the confluence with site 4 (Figure 4.1) was affected by the 2003 Lost Creek wildfire, which burned 21,000 ha of nearly contiguous forest land and had partial areas subsequently salvage logged between 2003 and 2005 (Silins et al., 2009). Four fully submerged gravel bars (Site 1 to 4) in the Crowsnest River were studied (Table 4.1, Figure 4.1). All gravel bars remained submerged throughout the sampling period.

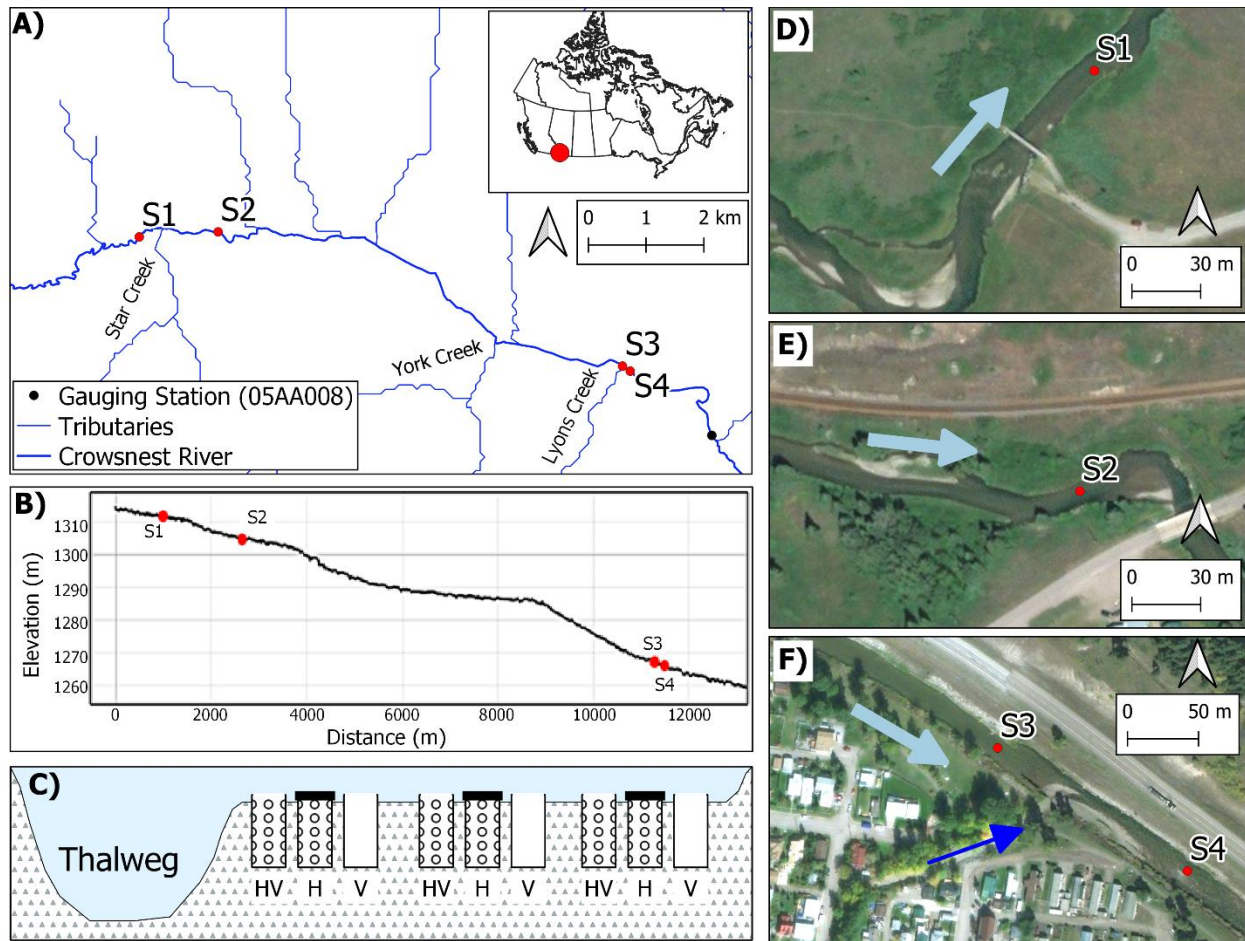


Figure 4.1: A) Location map; B) elevation map obtained with river channel topographic survey; C) schematics for sediment trap deployment, which was replicated at the four sites; D, E and F) Location of each gravel bar in relation to the closest upstream bend (lighter blue arrows over imagery indicate the flow direction in the Crowsnest River, darker blue arrows indicate flow direction in Lyons Creek).

Table 4.1. Characteristics of the studied gravel bars and summary of observed flow conditions.

	Site 1		Site 2		Site 3		Site 4	
<i>Bed slope</i>	$\sim 0.003 \text{ m m}^{-1}$		$\sim 0.005 \text{ m m}^{-1}$		$\sim 0.006 \text{ m m}^{-1}$		$\sim 0.006 \text{ m m}^{-1}$	
<i>Location within the gravel bar</i>	~70 m downstream of a bend		~10 m downstream of a bend		~100 m downstream of a bend		~100 m downstream of tributary confluence	
<i>D₁₀ gravel (mm)</i>	12		12		35		19	
<i>D₅₀ gravel (mm)</i>	24		41		82		70	
<i>D₉₀ gravel (mm)</i>	54		95		140		220	
<i>ϕ_{gravel} (% , mean $\pm$ s.d.)</i>	39.9 ± 2.2		38.6 ± 2.3		38.4 ± 3.5		38.5 ± 3.2	
	Mean	Min - Max	Mean	Min - Max	Mean	Min - Max	Mean	Min - Max
<i>VC (ppm)</i>	10.0	5.5 - 20.8	10.0	5.2 - 19.3	14.0	6.7 - 27.9	12.4	7.1 - 22.5
<i>TSS (mg l⁻¹)</i>	4.2	0.0 - 11.6	5.2	1.8 - 11.2	4.1	0.0 - 14.9	5.0	1.9 - 13.1
<i>Q (m³ s⁻¹)</i>	4.2	2.2 - 6.0	4.5	2.3 - 6.6	5.9	3.0 - 10.0	6.4	3.2 - 11.1
<i>d (m)</i>	0.6	0.5 - 0.8	0.6	0.4 - 0.8	0.7	0.5 - 0.9	0.6	0.4 - 0.9
<i>Fr</i>	0.3	0.3 - 0.6	1.0	0.7 - 1.8	0.6	0.5 - 0.9	0.7	0.5 - 1.1
<i>τ_0 (Pa)</i>	21.6	16.3 - 26.3	18.0	13.2 - 21.9	20.5	15.7 - 26.2	18.6	14.4 - 27.0
<i>ω (W m⁻²)</i>	15.1	8.5 - 20.9	34.2	24.6 - 50.3	24.3	15.0 - 35.6	26.2	15.8 - 39.4

4.3.2. Sampling programme and experimental design

Hydro-sedimentological data (discharge, particle size distribution (PSD), TSS, and volume concentration – VC of suspended solids) were collected every ~2 days at each site from June 18 to July 19, 2021. Discharge was measured with a FlowTracker2 (SonTek, Yellow Springs, OR, USA) at sites 1 and 4 and three tributaries (Star Creek, York Creek, and Lyons Creek; Figure 4.1) to estimate discharge at sites 2 and 3 (Figure 4.2). A dendrogram was built for the assessed hydro-sedimentological parameters, and this allowed deployment cycles (discussed below) to be grouped between higher (cycles 1, 2 and 3) and lower (cycles 4, 5, 6 and 7) discharge events (HQ and LQ, respectively; Figure C.1). TSS was sampled with 500 ml Nalgene bottles using a DH-48 sampler and measured following the Standard Methods Procedure (APHA 1995). VC and PSDs of suspended solids <0.5 mm were assessed *in-situ* with a LISST-200x (Sequoia Scientific, Bellevue, WA, USA). Additional hydraulic parameters (water depth, bed shear stress, unit stream power, and

Froude number) at the four sites were obtained through a calibrated flow model (MOBED; discussed below) (Krishnappan, 1981). Fine sediment ingress was measured using sediment ingress traps deployed over seven cycles (Figure 4.2) to assess ingress rates, directional ingress mechanisms, and the particle size distribution of ingressed particles. Framework porosity at each site was calculated using deployed ingress traps (discussed below).

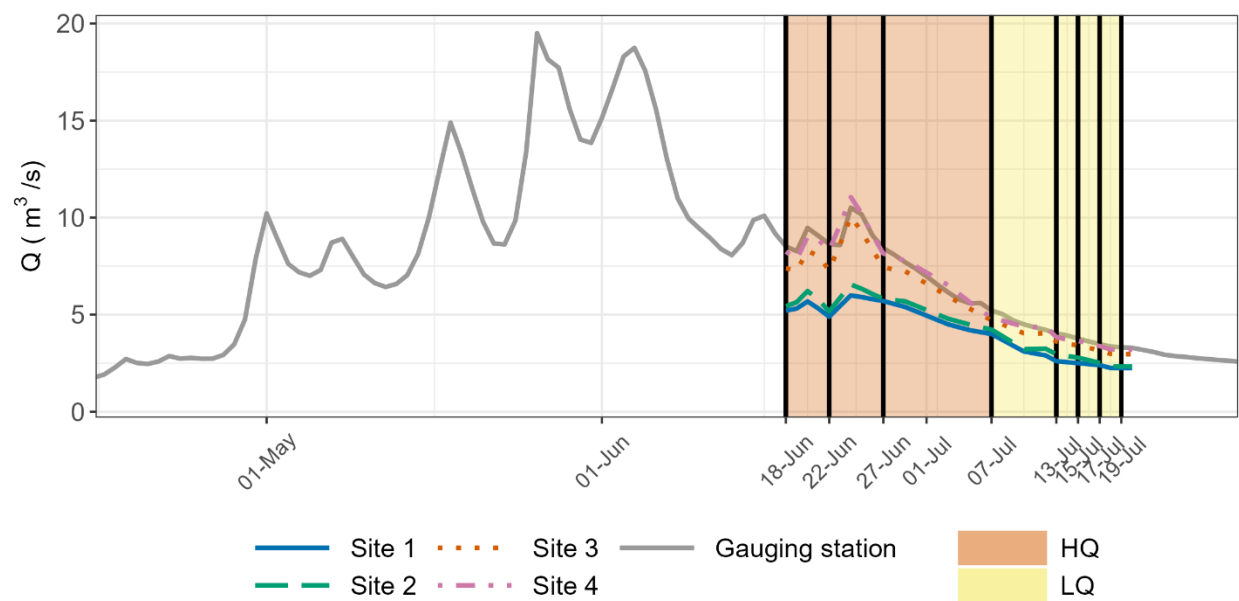


Figure 4.2: Measured discharge at the study sites in relation to discharges in the Crowsnest River at the Frank gauging station (05AA008). Vertical lines indicate the time delimitation of each ingress trap deployment cycle.

4.3.3. Assessment of fine sediment ingress

Fine sediment ingress mechanisms were assessed through the deployment of three types of ingress traps (Figure 4.1): a) Lidless impermeable-walled traps (herein denoted as vertical – V), which allowed fine sediment to accumulate only through the open surface area, measuring vertical ingress; b) Lidded permeable-walled traps (herein denoted as horizontal – H), which allowed fine

sediment to ingress only through lateral openings, measuring horizontal ingress, and; c) Lidless permeable-walled traps (herein denoted as horizontal-vertical – HV), which permitted measurement of both horizontal and vertical ingress. Traps were deployed in triplicates, and at the end of each deployment cycle, deployed traps were replaced with new ones simultaneously at all sites. Ingress traps were assembled similarly to the samplers used by Casas-Mulet et al. (2017) using 32 oz deli containers (surface diameter of 11.43 cm and height of 13.97 cm). Lateral openings on HV and H traps were 1 cm diameter (20 holes per trap). Prior to installation, traps were filled with local and sieve-washed gravel (>2 mm) (Figure 4.1C). A total of 252 traps (3 trap designs x triplicates x 4 sites x 7 cycles) were installed. Six traps were damaged and were not included in the ingress dataset. For pairwise comparisons, the six damaged traps and their pairs were also removed (for example, if Cycle 2, Site 2, H-C was damaged, we also removed Cycle 2, Site 2, HV-C and V-C).

After sediment trap retrieval, sediment from each trap was washed through 2 mm and 0.5 mm sieves, oven-dried, and weighed to calculate the mass of ingressed fine sediment in these size fractions. Ingress rates are commonly reported in the literature in units of $\text{kg day}^{-1} \text{m}^{-2}$ (mass of accumulated fine sediment by number of deployment days and channel surface area of accumulation). Here, such units of ingress rate were only reported for V traps since other trap designs have differing areas of accumulation. For HV and H trap designs, ingress rates were reported in units of kg day^{-1} .

Upon sediment trap retrieval, gravel (>2 mm) porosity (ϕ) was calculated as:

$$\phi = \left(\frac{m_w / \rho_w}{m_w / \rho_w + m_g / \rho_g} \right) 100 \quad (1)$$

where m_w is the mass of water (g), ρ_w is the density of water (1 g cm^{-3}), m_g is the mass of gravel (g), and ρ_g is the density of the gravel (2.6 g cm^{-3}).

While sieve-washing accumulated sediment $<0.5 \text{ mm}$, samples of $\sim 3 \text{ ml}$ of sediment and water mixtures were collected to measure effective and absolute PSDs (EPSD and APSD, respectively) with a LISST-200x. While the assessment of EPSDs could have led to the breakage of flocculated particles, especially for coarser, more loosely attached flocs, we still lack alternatives to assess non-dispersed distributions more efficiently. EPSDs of ingressed particle size distributions were grouped according to four size classes ($1 - 9$, $9 - 67$, $67 - 130$, and $130 - 500 \text{ }\mu\text{m}$) to be consistent with size classes reported in other studies (Harper et al., 2017; Mathers and Wood, 2016). Following size grouping, the relative VC of each size group was calculated relative to the total VC measured in each sediment trap ($\text{Relative VC} = \text{VC}_{\text{size class}} / \text{Total VC}_{<500 \text{ }\mu\text{m}}$).

4.3.4. Hydraulic parameters

MOBED is a one-dimensional, unsteady, mobile boundary flow model (Krishnappan, 1981). Inputs to MOBED include cross-sectional channel geometry, bed grain size distribution, initial bed and water surface elevations at each sectional grid, and boundary conditions of discharge and water depth at the first and last grids (Droppo et al., 2011; Stone et al., 2021b). Cross-sectional information at each grid ($n = 20$) was obtained through a detailed river channel topographic survey, where coordinates of bed elevation were measured every $\sim 20 \text{ m}$ (Figure 4.1B), and cross-sectional geometry was measured every $\sim 500 \text{ m}$ along the $\sim 10 \text{ km}$ study reach. Discharge and water depth were either measured on site or calculated using Manning's equation (NWS, 2023). Bed shear stresses were predominantly below the theoretical critical values for incipient motion of bed particles, calculated considering the framework D_{50s} at each site (Shields et al., 1936). Further,

field observations indicate that the armour layer was strong enough to prevent full bed mobility under the assessed flow conditions at all sites (Buffington and Montgomery, 1997). Accordingly, MOBED was set up assuming the non-mobility of the channel framework. In the MOBED model, friction factors (f) were calculated using Manning's relationships (Krishnappan, 1986). More detailed information on MOBED can be found in Krishnappan (1981, 1983, 1986). Here, MOBED outputs of flow area (A_w), flow depth (d), discharge (Q), top width of the flow (T), and friction factor (f) were used to calculate bed shear stress (τ_0), unit stream power (ω), and Froude number (Fr) daily during the study period at the four study sites. Bed shear stresses (Pa) were calculated as:

$$\tau_0 = u^{*2} \times \rho_w \quad (2)$$

$$u^* = \frac{\bar{u}}{f} \quad (3)$$

$$\bar{u} = \frac{Q}{A_w} \quad (4)$$

where ρ_w is the water density (1000 kg m^{-3}), u^* is the shear velocity (m s^{-1}) and $\bar{u}$ is the mean velocity (m s^{-1}). Unit stream power (W s^{-2}) was calculated as:

$$\omega = \tau_0 \cdot \bar{u} \quad (5)$$

Froude numbers were calculated as:

$$Fr = \frac{\bar{u}}{\sqrt{g \cdot D_w}} \quad (6)$$

$$D_w = \frac{A_w}{T} \quad (7)$$

where D_w is the hydraulic depth (m), and g is the acceleration due to gravity (9.81 m s^{-2}). Daily hydraulic parameters calculated with MOBED were selected to match the days in which our field assessments were performed and were averaged – along with measured discharge, TSS, and VC – for each ingress trap deployment cycle. Accordingly, an averaged value for each hydro-sedimentological variable was obtained for each deployment cycle and site, which were then statistically related to the measured ingress rates.

4.3.5. Statistical analyses

A series of linear mixed-effects models (LME) were applied to the dataset. LME models allow the assessment of effects from both fixed and random factors on the dependent variable (ingress rates). Incorporating clustering effects (random factors), defined in all models by each study site, reduces overall model variability by accounting for similarities within clusters (Harper et al., 2017; Mathers and Wood, 2016). The first set of LME models was applied to assess the effects of each hydro-sedimentological parameter on ingress rates (measured with HV traps). Another set of LME models was applied to assess the effects of each hydro-sedimentological parameter and their interactions with ingress mechanisms (measured with V and H traps) on ingress rates. The LMEs were applied separately for each size class ($<0.5 \text{ mm}$ and $0.5 - 2 \text{ mm}$). Prior to modelling, ingress rates were log-transformed, centered around means, and scaled with respect to standard deviation (normalized ingress rates).

Further, linear regressions were applied to assess the relationships between hydro-sedimentological parameters and ingress mechanisms for ingress rates of $<0.5 \text{ mm}$ particles. Since LME results regarding the $0.5 - 2 \text{ mm}$ size class presented poor model fits, linear regressions were only performed regarding the finer size class. Further, it has been previously observed that the

ingress of sands can stimulate the interstitial accumulation of finer sediment (Naden et al., 2016; Warren et al., 2009). To assess the influence of sands on the ingress of the <0.5 mm size class, linear regression was also applied using ingress rates from HV traps.

All statistical analyses and graphing were performed using R Statistical Software (R Core Team, 2022) through the RStudio Integrated Development Environment (RStudio Team, 2022). LME models were fitted using the “lme4” package (Bates et al., 2015) with the restricted maximum likelihood estimation function. Conditional and marginal R^2 values from the LMEs were extracted using the “MuMIn” package (Bartoń, 2023). ANOVA (type 2 with Wald χ^2 statistics) was used to assess the predictors’ significance with the “car” package (Fox et al., 2023). Pairwise comparisons were performed with the “rstatix” package (Kassambara, 2021). All graphs were plotted using the “ggplot2” (Wickham, 2016) and “ggpubr” (Kassambara, 2020) packages.

4.4. Results

Total ingress rates (<2 mm) in the Crowsnest River were 0.005 ± 0.003 (average $\pm$ SE) kg day⁻¹, ranging from 0.0012 to 0.0207 kg day⁻¹ (HV traps, Figure 4.3), and ingress rates per accumulation area (V traps) were 0.44 ± 0.32 (average $\pm$ SE) kg m⁻² day⁻¹. No surficial sediment deposition or interstitial clogging was observed near or on top of deployed sediment traps for all assessments. The highest accumulation rates were observed during cycle 2 and the lowest during cycle 7 (Figure 4.3A). The masses of ingressed sediment for both sediment size classes (<0.5 and 0.5 – 2 mm) were significantly (Mann-Whitney U test, $p < 0.001$) higher during HQ ($n = 36$) relative to LQ ($n = 48$), but ingress rates were only significantly (Mann-Whitney U test, $p < 0.001$) higher in HQ relative to LQ for sediments <0.5 mm (Figures C.2 and C.3).

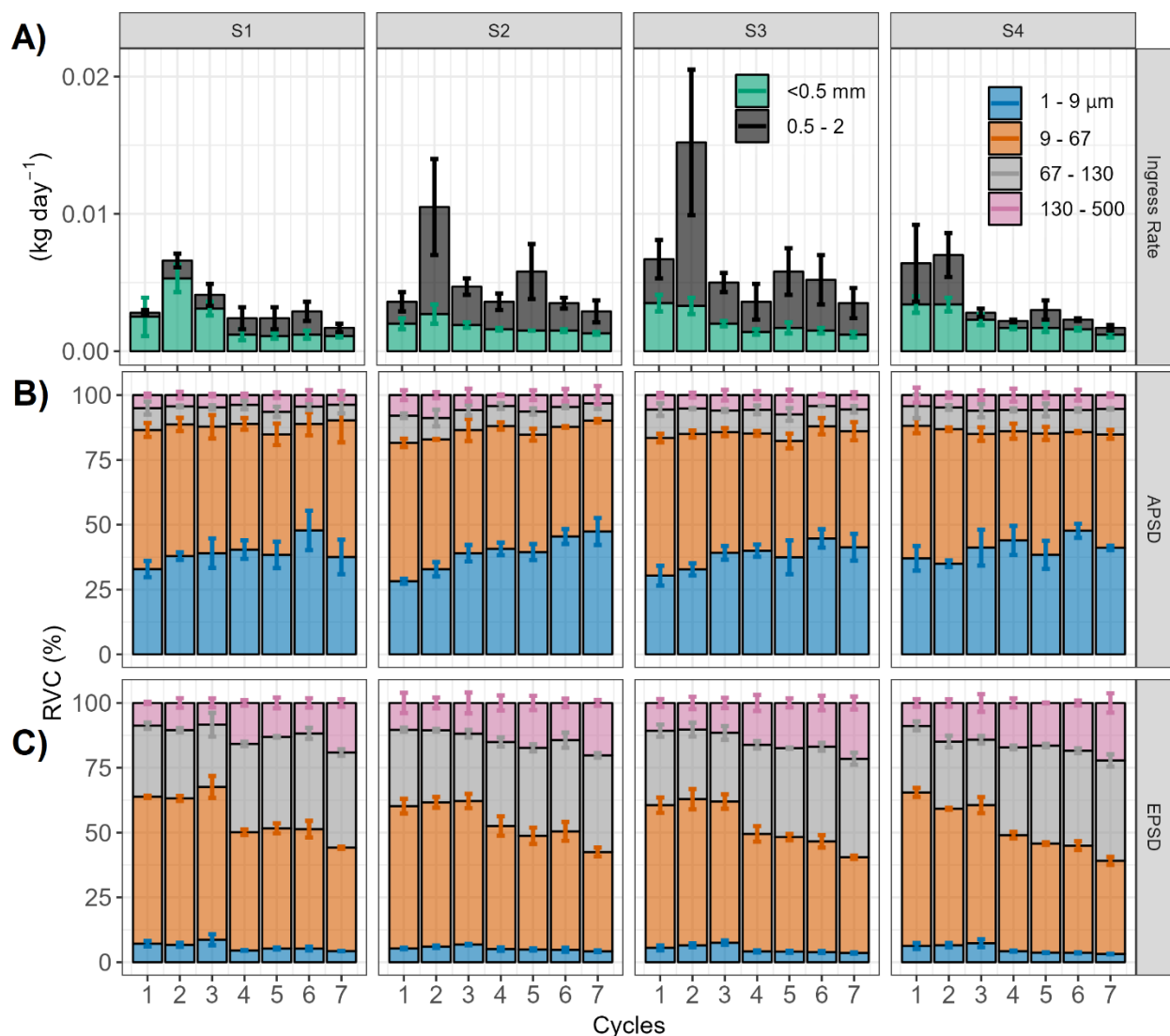


Figure 4.3. Mean $\pm$ SD of A) ingress rates, B) relative volume concentration (RVC) for absolute particle size distributions (APSDs), and C) RVC for effective particle size distributions (EPSDs) using HV sediment traps.

The assessment of APSDs and EPSDs demonstrated that particles <0.5 mm were consistently flocculated regarding suspended (D_{50} EPSD = $54.5 \mu\text{m}$ and D_{50} APSD = $18.6 \mu\text{m}$) and ingressed (D_{50} EPSD = $59.4 \mu\text{m}$ and D_{50} APSD = $14.4 \mu\text{m}$) sediment (Figure 4.4). Particle size assessment for ingressed particles <0.5 mm demonstrated that, while dispersed particles were predominantly within size classes of $1 - 9$ and $9 - 67 \mu\text{m}$ (Figure 4.3B), flocculated particles were predominantly

within effective size classes of 9 – 67, and 67 – 130 μm (Figure 4.3C). The relative VC of dispersed particles $>67 \mu\text{m}$ corresponded to only $\sim 14\%$ of all sediment $<0.5 \text{ mm}$ (Figure 4.3B). The relative VC of effective sizes in classes 67 – 130 and 130 – 500 μm were significantly (Mann-Whitney U test, $p < 0.001$) higher in LQ ($n = 48$) compared to HQ ($n = 36$), and, accordingly, size classes of 1 – 9 and 9 – 67 μm were higher in HQ ($p < 0.001$) (Figure C.4).

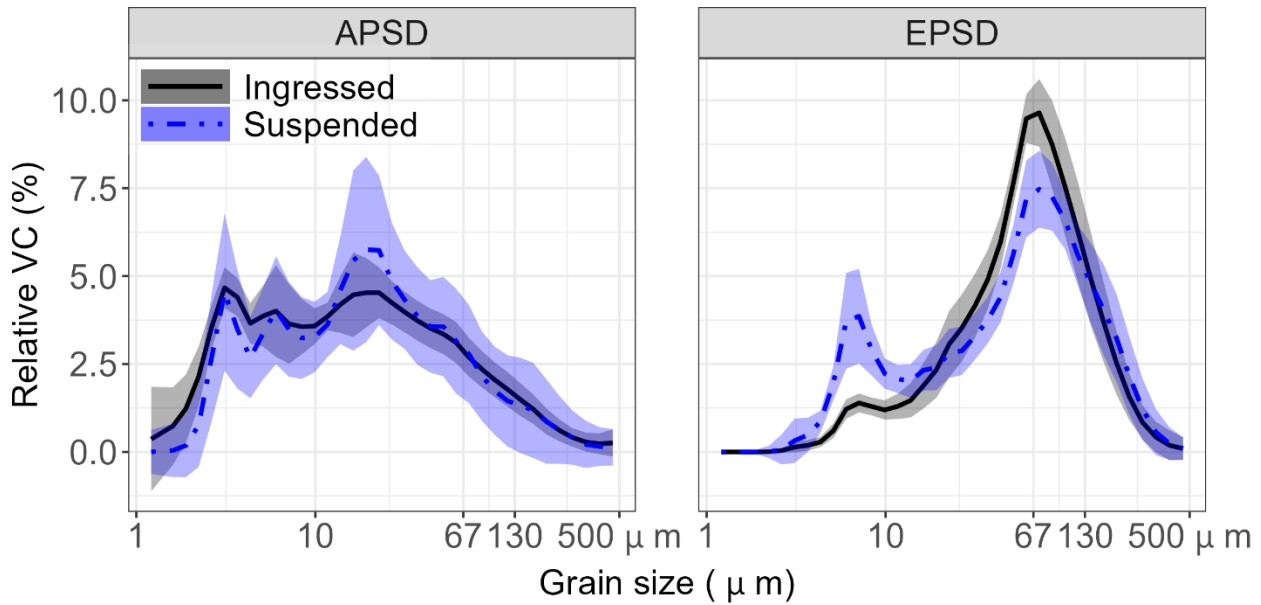


Figure 4.4. Absolute and effective particle size distributions of ingressed (measured on HV traps) and suspended sediment. Lines represent median of all measurements ($n_{\text{suspended}} = 112$, $n_{\text{ingressed}} = 84$ for each absolute and effective distributions), and shaded areas represent $\pm 1 \text{ SD}$.

Higher variability in ingress rates was observed regarding the 0.5 – 2 mm size class (Figure 4.3A). Accordingly, all LME models applied for the 0.5 – 2 mm size class presented goodness-of-fit $< 70\%$, and model variances were mostly explained through the random effects of sites (difference between marginal and conditional R^2 ; Table 4.2). In regards to the $< 0.5 \text{ mm}$ size class, which mostly consisted of flocculated particles, the interaction between ingress directional

mechanisms and the parameters VC, τ_0 , and ω , presented conditional $R^2 > 70\%$ (models assessing TSS, Q, and water depth presented conditional $R^2 > 60\%$) (Table 4.2). For flocs < 0.5 mm, differences between marginal and conditional R^2 demonstrated that, although the clustering effects of sites improved the goodness-of-fit, this effect produced weaker responses on ingress in comparison with the 0.5 – 2 mm size class (Table 4.2).

Table 4.2. Summary of the LME models examining fine sediment ingress rates according to ingress mechanism and hydro-sedimentological parameters (and their interactions) for < 0.5 and 0.5 – 2 mm sizes classes (m corresponds to marginal R^2 , c corresponds to conditional R^2). Bold p-values represent significant results at the 95% confidence level, bold conditional R^2 represent models with goodness-of-fit > 0.7 .

Predictors	<0.5 mm				0.5 - 2 mm			
	χ^2	p-value		R^2	χ^2	p-value		R^2
Mechanism	19.49	<0.001	m	0.107	0.40	0.526	m	0.001
			c	0.121			c	0.532
VC	266.95	<0.001	m	0.577	0.02	0.886	m	0.003
VC:Mechanism	26.76	<0.001	c	0.713	0.88	0.348	c	0.531
TSS	231.96	<0.001	m	0.594	6.87	0.009	m	0.023
TSS:Mechanism	17.96	<0.001	c	0.627	1.03	0.310	c	0.548
Q	238.19	<0.001	m	0.571	2.84	0.092	m	0.012
Q:Mechanism	24.25	<0.001	c	0.697	1.04	0.308	c	0.541
Depth	241.86	<0.001	m	0.567	1.46	0.228	m	0.006
Depth:Mechanism	32.53	<0.001	c	0.689	0.59	0.442	c	0.528
Fr	0.03	0.859	m	0.107	0.08	0.775	m	0.007
Fr:Mechanism	19.73	<0.001	c	0.134	1.06	0.303	c	0.544
τ_0	351.36	<0.001	m	0.637	0.59	0.441	m	0.003
τ_0 :Mechanism	41.18	<0.001	c	0.778	0.45	0.503	c	0.537
ω	262.34	<0.001	m	0.472	2.59	0.107	m	0.022
ω :Mechanism	33.64	<0.001	c	0.875	1.38	0.239	c	0.507

Pairwise comparisons between the two ingress mechanisms according to size class showed that ingress was predominantly horizontal for particles < 0.5 mm under both flow conditions,

although significant differences were mostly observed during LQ (Figure 4.5). For particles 0.5 – 2 mm, ingress was mostly due to vertical mechanisms during HQ, although for most sites and flow conditions the differences were not significant (Figure 4.5). Linear regressions performed for particles <0.5 mm showed positive correlations between hydro-sedimentological drivers and ingress rates for both mechanisms (Figure 4.6). The linear regressions pertaining to vertical mechanisms seemed to present higher slopes than the horizontal mechanisms, but R^2 values for horizontal mechanisms were generally too low to confirm this relationship (Figure 4.6). Positive relationships between ingress rates of finer and coarser fractions of fine sediment were observed for sites 2, 3 and 4, but the corresponding R^2 were all <40% (Figure 4.7).

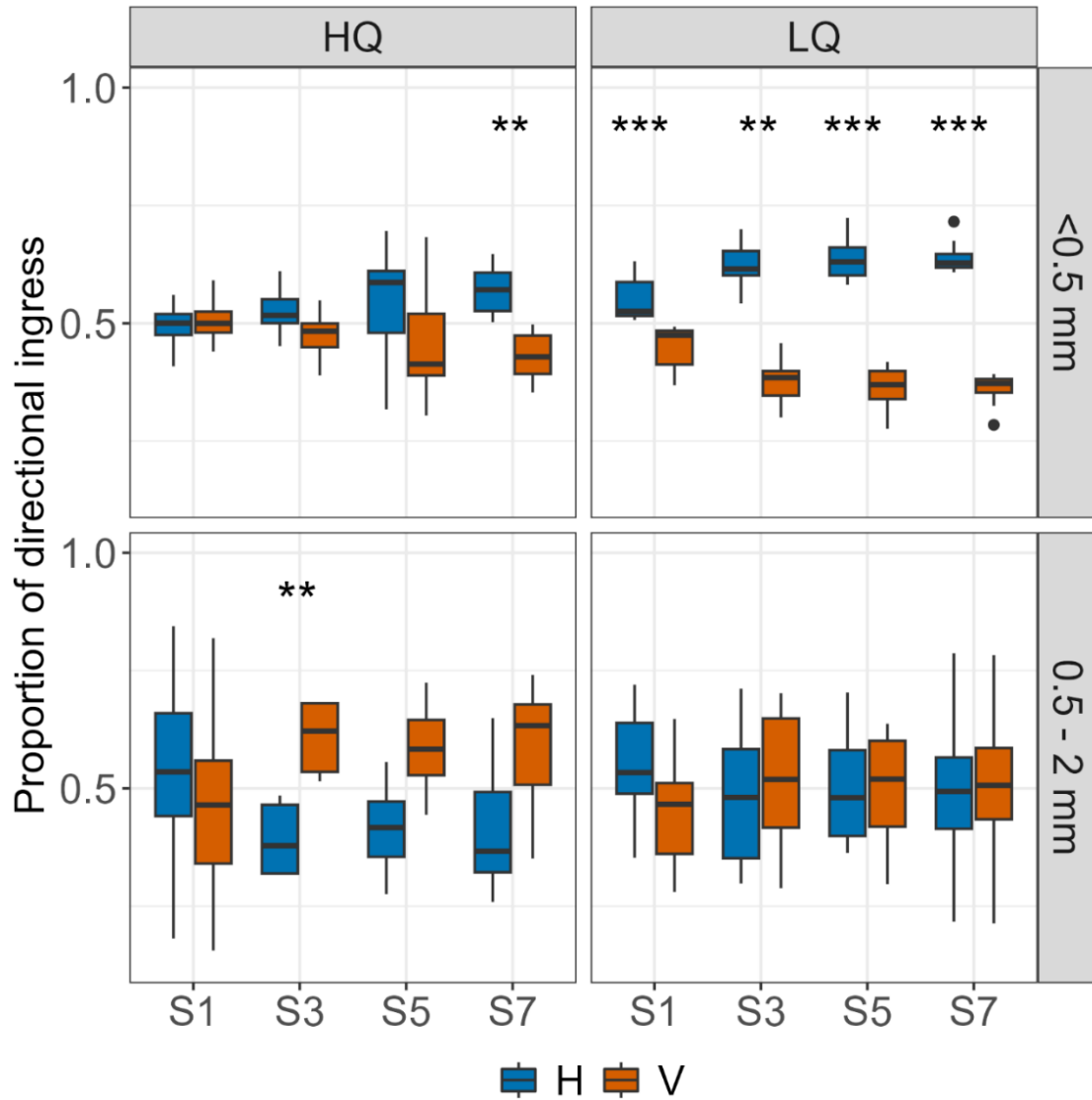


Figure 4.5. Wilcoxon signed rank test pairwise comparison at higher energy flow conditions (HQ) and lower energy flow conditions (LQ) between ingress mechanisms ($n = 9$ for each design of ingress trap during HQ, $n = 12$ for each design of ingress trap during LQ). Proportions indicate $H + V = 1$. Adjusted (Benjamini-Hochberg) p-values: ** $p < 0.01$, and *** $p < 0.001$. Median, upper, and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range.

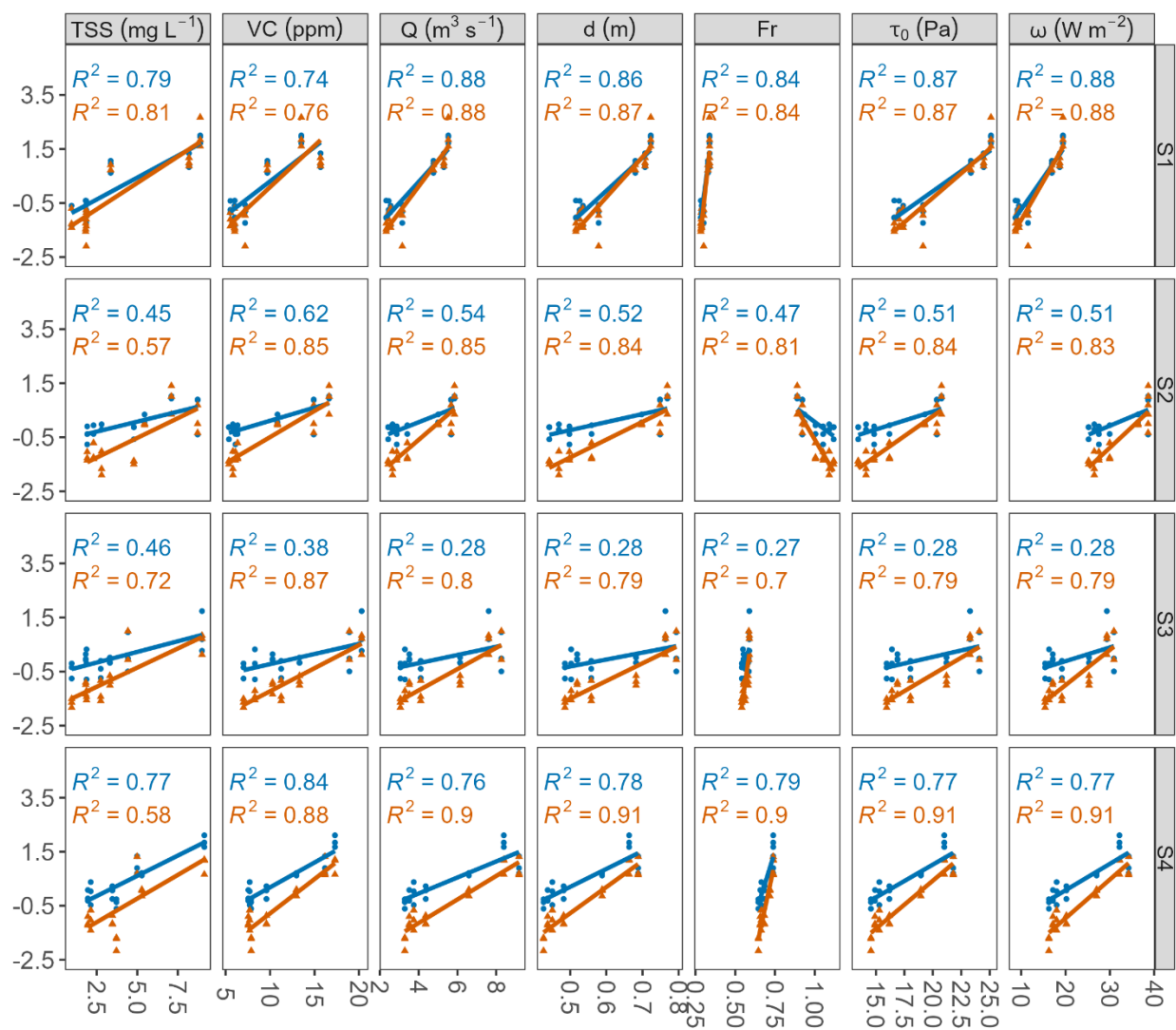


Figure 4.6. Linear regressions of normalized ingress rates as a function of hydro-sedimentological parameters for the <0.5 mm size class for different ingress mechanisms. Normalized ingress rates in the y-axis, blue dots and orange triangles indicate data from H and V traps, respectively. All p-values <0.05.

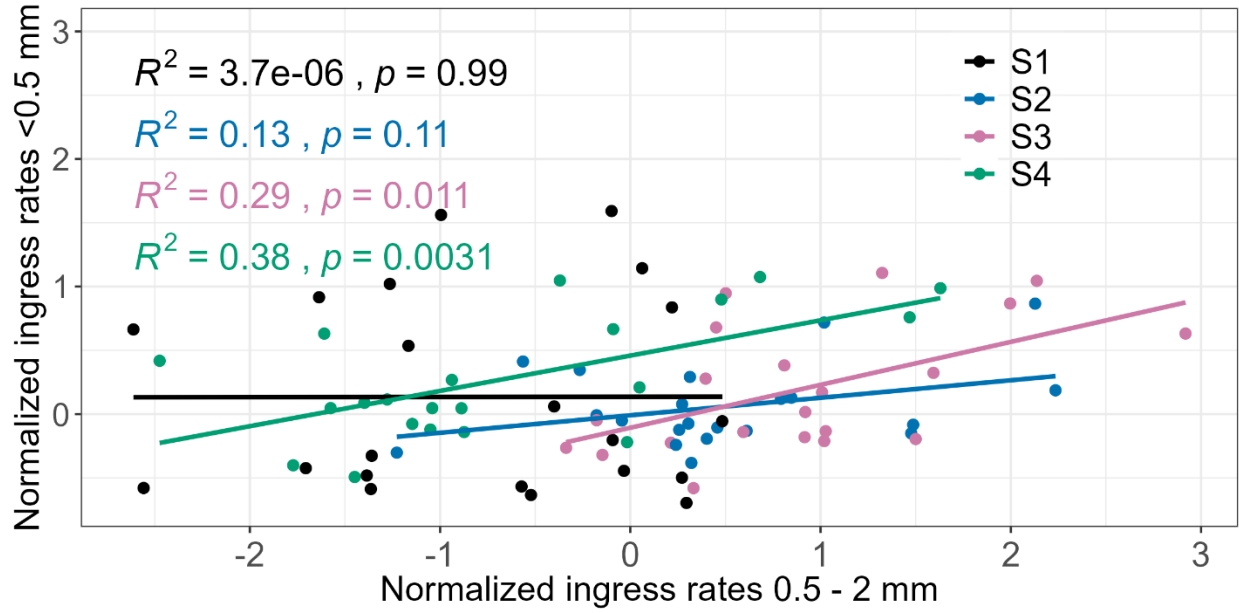


Figure 4.7. Relationships between the ingress rates of coarser and finer size classes regarding the measurements taken using HV ingress traps.

4.5. Discussion

4.5.1. Drivers of interstitial fine sediment accumulation

The fraction of sediment <0.5 mm in our assessments was observed to be predominantly flocculated. The flocculated characteristics of cohesive fine sediment alter the transport properties (porosity, setting velocity, and particle size distribution) of these particles (Droppo, 2001; Droppo and Ongley, 1992; Krishnappan, 2007; Krishnappan and Engel, 2006), which, in turn, affect its interactions with the gravel-bed. Accordingly, our observations on the contrasting behavior of <0.5 and 0.5 – 2 mm particles demonstrate the role of flocculation on the ingress characteristics of fine sediment.

Regarding the non-cohesive 0.5 – 2 mm size fractions, none of the assessed hydro-sedimentological parameters significantly affected ingress rates (Table 4.2). Conversely, Beschta

and Jackson (1979) found a good correlation between Froude numbers and the ingress of sands (0.5 mm). However, the experimental setup conducted by Beschta and Jackson (1979) evaluated considerably higher fine sediment concentrations (~ 1000 to 10000 mg L^{-1}). Casas-Mullet et al. (2017) assessed total fine sediment ingress $< 2 \text{ mm}$ and reported good correlations between ingress rates and water levels, suspended sediment concentration, and bed shear stress. Their observations, however, were not limited to linear relationships between hydro-sedimentological parameters and ingress rates (Casas-Mullet et al., 2017). The absence of correlations observed in the present study for the coarser class of fine sediment is in accordance with the observations of Carling (1984). While evaluating ingress rates of fine sands ($\sim 0.15 \text{ mm}$), Carling (1984) observed that mean flow hydraulic parameters, like those assessed in our study, had little effect on processes occurring near and within the interstices of the channel bed. The LME results regarding the $0.5 - 2 \text{ mm}$ size class showed the importance of the clustering effect of sites in improving model fits, demonstrating the importance of site-specific characteristics on the ingress of this size group. Accordingly, the high variability in measurements, which can be attributed to both natural variability and assessment limitations imposed by the samplers (Maltauro et al., 2024), can further corroborate the poor relationships observed in the LME models for the $0.5 - 2 \text{ mm}$ size class.

Conversely, the LME results showed that most of the assessed parameters (except by Froude number; Table 4.2 and Figure 4.6) were important in controlling ingress rates of the $< 0.5 \text{ mm}$ fine sediment. To the best of our knowledge, no other studies have assessed hydro-sedimentological drivers for the ingress of flocculated fine sediment. The linear regressions regarding the $< 0.5 \text{ mm}$ size class showed that both flow related parameters (Q , d , τ_0 and ω) and suspended sediment-related parameters (TSS and VC) were positively correlated with ingress rates at all sites. Likewise, in the Crowsnest River, discharge was positively correlated with suspended sediment

concentrations ($R^2 > 0.75$ and $p < 0.05$) at all sites, which is in accordance with other studies conducted in the region (Maltauro et al., 2023; Silins et al., 2009, 2008). Accordingly, it is not possible to inform the extent to which ingress rates increased because of increasing flow energy or the higher suspended sediment availability during HQ. Previous studies have observed the mutual importance of both sediment supply and hydraulic energy. For instance, studies such as the ones of Beschta and Jackson (1979) and Schälchli (1992) showed maximum ingress occurring under high energy flows, just below the threshold of bed framework entrainment, attributing such increase in sediment intrusion to the vibration on the gravel surface caused by turbulent flows. Under high sediment supply and low energy flows, Shrivastava et al. (2020) observed that increasing cohesive sediment suspended concentrations resulted in surficial clogging due to the cohesive forces acting on gravel interstices, impeding further ingress from occurring. In their study, the concentration leading to surficial clogging was comparable to the concentrations observed in our study. However, the gravel framework in our sites was much coarser compared to their flume experiment (Shrivastava et al., 2020). Nonetheless, further investigation in the Crowsnest River is required to assess ingress rates under other flow conditions, such as during snowmelt or under sporadically high suspended sediment concentrations.

Previous studies in the Crowsnest River reported that, under flow conditions comparable to those observed in this study, suspended solids < 0.5 mm were mainly transported in flocculated form (Maltauro et al., 2023). Likewise, our assessments showed that ingressed particles < 0.5 mm were also predominantly flocculated. Modal similarities between EPSDs and APSDs of suspended and ingressed particles (Figure 4.4) demonstrate the same nature (source) of particles, and the lower modal peak (~ 8 μm) for ingressed particles can be attributed to either flocculation of this size class into larger flocs (given lower pore water energy and the higher second mode at ~ 67 μm),

or to a preferential ingress of coarser suspended flocs. Further, ingressed flocs 67 – 500 μm were relatively more abundant during LQ conditions (Figure C.3), indicating that flocculation can be favoured in such conditions. Given the observed agreement between the ingress of <0.5 mm particles with hydro-sedimentological drivers (Table 4.2, Figure 4.6) and knowing that flocculation decreases particle density (Glasbergen et al., 2015; Krishnappan, 2022; Krishnappan and Engel, 2006), we infer that the resulting floc density is allowing the flow field to act as a key driver on the ingress of flocs.

4.5.2. The dynamics of fine sediment ingress directional mechanisms

Fine sediment and gravel-bed channel interactions have been predominantly evaluated by assessing vertical fine sediment ingress (e.g., Beschta and Jackson, 1979; Frostick et al., 1984; Wood and Armitage, 1999; Franssen et al., 2014). Horizontal ingress mechanisms, however, have been observed to be an important driver of interstitial fine sediment accumulation (Carling, 1984; Casas-Mulet et al., 2017; Harper et al., 2017; Mathers and Wood, 2016; Petticrew et al., 2007). For our study, approximately 52% of accumulated fine sediment <2 mm was due to horizontal accumulation. Horizontal accumulation represented $\sim 58\%$ when considering particles <0.5 mm and $\sim 48\%$ for particles 0.5 – 2 mm. These values are comparable to the results of Casas-Mulet et al. (2017) but are higher than the $\sim 30\%$ horizontal contribution reported elsewhere (Carling, 1984; Mathers and Wood, 2016; Sear, 1993).

The predominance of either horizontal or vertical ingress mechanism, however, was observed to depend on flow conditions, especially for sediment <0.5 mm. The increased occurrence of vertical ingress mechanisms during higher flows was consistently observed for all size classes (Figure 4.5). Based on previous observations, we believe that the higher vertical

accumulation for all particle sizes was caused by the ingress from both suspended load and fine fractions of the bedload due to turbulence effects during higher energy flows (Brunke, 1999; Frostick et al., 1984; Schälchli, 1992). Vertical accumulation during higher flows was particularly elevated in the case of the 0.5 – 2 mm size class, which is non-cohesive and presents high particle density ($\sim 2.6 \text{ g cm}^{-3}$). We believe that for this coarser size fraction, higher density allowed particles to enter ingress traps and settle downwards through unimpeded static percolation (Gibson et al., 2009; Herrero and Berni, 2016), a mechanism that likely prevented their exfiltration from V traps since any exfiltration in such traps would have been limited to the top layer of the containers (Detert and Parker, 2010; Kuhnle et al., 2016). The lack of significant differences between directional mechanisms can be attributed to the high variability of observations from both H and V traps and further corroborates the limitation of the samplers to assess particles 0.5 – 2 mm.

Regarding the <0.5 mm size classes, we believe that smaller differences between vertical and horizontal mechanisms during higher energy flows (Figure 4.5) were caused not only by elevated vertical accumulation from suspended load but also by the occurrence of horizontal exfiltration in H traps. High energy flows can lead to turbulent mixing near the sediment-water interface, introducing pore water velocity (Packman et al., 2004; Reidenbach et al., 2010; Tonina and Buffington, 2009) and horizontal interstitial fine sediment transport (Carling, 1984; Casas-Mulet et al., 2017; Petticrew et al., 2007). As previously discussed, <0.5 mm particles have their transport linked to the flow field due to decreased floc density, thus leading us to believe that higher horizontal exfiltration occurred during HQ compared to LQ. Although lower energy flows might have decreased the turbulence effects leading to vertical accumulation (either due to lower energy or the low sediment supply), near-bed turbulence was likely still high enough to introduce pore water flow and promote horizontal accumulation. Furthermore, the linear regression analyses

suggest that the curves pertaining vertical accumulation presented higher slopes relative to horizontal mechanisms (except for Froude numbers, Figure 4.6). This observation suggests that, while ingress rates are predominantly horizontal during LQ, increases in flow energy may lead to a more accelerated increase in vertical mechanisms. It is important to note, however, that R^2 values regarding the curves of horizontal mechanisms were generally low, indicating a degree of uncertainty in this interpretation.

4.5.3. The impacts and legacy effects of interstitial fine sediment

Ingress rates measured in this study exceeded those observed in areas with highly vegetated riparian zones (Mathers and Wood, 2016) but were comparable to others impacted by upstream disturbances (Harper et al., 2017; Petticrew et al., 2007). For further comparisons, a summary of ingress rates measured in the literature can be found in Casas-Mulet et al. (2017) and Sear (1993). Excess amounts of fine streambed sediment can lead to saturation of the gravel framework and interstitial clogging (see Wharton et al., 2017), which can decrease framework permeability and hydraulic conductivity (Brunke, 1999; Schälchli, 1992), thereby reducing hyporheic exchanges (Packman and MacKay, 2003), affecting spawning sites and development of the embryos of lithophilic fish (Greig et al., 2005; Havis et al., 1993; Kemp et al., 2011). Due to its deleterious impacts, streambed saturation by fine sediment and interstitial clogging have received increasing attention in studies investigating mechanisms driving fine sediment ingress (Gibson et al., 2009; Herrero and Berni, 2016; Schälchli, 1992; Wooster et al., 2008). During the study period, no near-saturation or clogging was observed within the flow and sediment supply conditions in the Crowsnest River. The $d_{15\text{framework}}/d_{85\text{sediment}}$ ratios were all well above the clogging thresholds proposed by Gibson et al. (2009), and it is likely that ratios between suspended load and ingress

rates minimized excess streambed accumulation (Beschta and Jackson, 1979; Frostick et al., 1984; Shrivastava et al., 2020; Wooster et al., 2008). Kinematic sieving (ingress during events of framework reworking) has also been observed to increase fine sediment accumulation and prevent clogging formation (Bacchi et al., 2014; Dudill et al., 2017), but because of the high bed stability in the Crowsnest River, kinetic sieving is most likely not a driver of sediment ingress. Previous studies reported that ingressing sands can stimulate the accumulation of finer particles, thus augmenting the risk of clogging (Naden et al., 2016; Warren et al., 2009). Here, we found positive relationships between the ingress rates of the <0.5 and 0.5 – 2 mm size class for sites 2, 3, and 4; however, correlations were weak ($R^2 < 0.4$) for all observations.

The lack of clogging is a positive aspect of the health of the Crowsnest River. The lack of clogging suggests that interstitial fine sediment flushing might not be limited to high-energy events leading to bed mobilization (Schälchli, 1992), and, as such, future investigations on sediment exfiltration mechanisms are still required. Moreover, the lack of clogging can also indicate the river's potential for storage capacity, especially given its highly stable streambed, in which gravel mobilization and fine sediment flushing (Schälchli, 1992) are limited to infrequent high discharge events. Here, we observed the important contribution of cohesive suspended sediment on interstitial fine sediment accumulation. These cohesive particles are well known for their binding properties with a range of pollutants mobilized from upstream landscape disturbances that can ingress and be stored in sediment-associated forms (Collins and Walling, 2007a; Walling et al., 2003; Walling and Collins, 2005). Thus, gravel-bed rivers can potentially extend the temporal duration of upstream disturbance effects until fine sediment exfiltration occurs (Walling et al., 2003).

In the Crowsnest River watershed, the 2003 Lost Creek wildfire produced long-lasting impacts on fine suspended sediment dynamics (Emelko et al., 2011; Silins et al., 2009), and recent assessments in the main channel of the Crowsnest River have observed downstream increases in interstitial particulate bioavailable phosphorus forms due to the compound effects of anthropogenic and climate-change exacerbated landscape disturbances (Watt et al., 2021). As such, our observations point to the high potential for downstream legacy effects following infrequent high discharge events in the Crowsnest River. In turn, the legacy impacts of landscape disturbances, which increase sediment supply from various watershed sources, point to the need to combine both source control and in-channel sediment exfiltration interventions to help manage the fine sediment problem. Without both, and especially the latter, current elevated levels of interstitial fine sediment will persist with variable implications for both benthic ecology and water quality.

4.6. Conclusions

We observed important differences in ingress properties according to different flow conditions and particle sizes. The assessed hydro-sedimentological parameters correlated poorly with ingress rates for the coarser fractions (0.5 – 2 mm) of fine sediment, but better correlations (except for the Froude number) were observed regarding the finer fractions of fine sediment. Higher ingress rates were measured during higher-energy flows, but we could not distinguish if that occurred solely because of the increased turbulence near the sediment-water interface or because of the higher suspended solids concentration during such flows. Differences between size classes are likely due to the cohesive properties of particles <0.5 mm (effective size), which are

mostly transported as flocculated particles in the Crowsnest River. Horizontal ingress mechanisms played an important role in the accumulation of interstitial fine sediment, especially for flocs.

Here, all measured discharges at the four sites during the study period resulted in bed shear stresses above the critical condition for fine sediment <2 mm deposition (Shields et al., 1936). Accordingly, no fine sediment surficial deposition was observed in any of the four sites, indicating that ingress was predominantly due to advective and/or turbulent mixing. Our observations exemplify that gravel-bed rivers can store a considerable mass of interstitial fine sediment, which can postpone and extend the effects of upstream landscape disturbances. This supports the importance of ingress mechanism for interstitial fine sediment accumulation and evidences the need to incorporate such mechanisms explicitly in fine sediment transport models. Future investigations are required to better understand the role of sediment exfiltration and re-ingress to improve our knowledge of legacy impacts arising from landscape disturbances in the catchments of gravel-bed rivers.

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Chapter 5. Evaluating Effective Particle Size Distributions of Cohesive Sediment under Varying Shear Stress and Bed Configurations in a Rotating Annular Flume

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5.1. Summary

In Chapter 5, a rotating annular flume was used to evaluate the effective particle size distribution characteristics of suspended solids according to different flow conditions and bed configurations in deposition, ingress, and erosion experiments. The results from Chapter 5 demonstrated the distinguishing effective particle size distributions pertaining to different channel bed configurations. While particle size distributions in the deposition experiments reached a stable flocculation state for all applied shear stresses, particle size distributions in the ingress experiment presented varying modal distributions throughout the experiment. The evaluation of flume and field particle size distributions demonstrated that flocculation was predominantly stimulated by increasing flow energy within the discharges observed in our assessments. Further, flume assessments demonstrated that coarser flocs were preferentially stored in the bed for both deposition over smooth and gravel-bed configurations.

5.2. Introduction

Cohesive sediments (organic and inorganic particles $< 63 \mu\text{m}$) are important vectors for the transport of many nutrients and contaminants in aquatic systems (Chapman et al., 2013; Horowitz and Elrick, 1987). Accordingly, excess amounts of fine sediment and associated pollutants can

alter the chemical, physical, and biological processes in rivers (Bilotta and Brazier, 2008; Chapman et al., 2014; Wilkes et al., 2019; Wood and Armitage, 1997). Primary particles of cohesive sediment flocculate with other mineral particles and a range of organic compounds and bacteria, forming flocs due to collision mechanisms in the flow field (Droppo et al., 1997; Droppo and Ongley, 1992; Lick et al., 1992). Relative to primary particles, flocculation alters effective (flocculated) particle size distributions (EPSDs), particle shape, density, porosity, and settling velocities of flocs (Droppo, 2001; Droppo and Ongley, 1992; Lick et al., 1992; Petticrew and Biickert, 1998; Williams et al., 2008). Compared to dispersed primary particles, flocculation can increase the settling velocities of flocs by one to two orders of magnitude (Krishnappan, 2022; Lamb et al., 2020; Livsey et al., 2022). Given that most transport parameters (e.g., density, settling velocity) of flocculated particles change as a function of floc size (Winterwerp, 1998), and given available laser diffraction methodologies to measure in situ EPSDs reliably, understanding the dynamics of EPSDs under varying environments and flow conditions is crucial for progressing the understanding of cohesive sediment transport. Despite the existing literature on flocculation, this process has not been sufficiently quantified for a range of particulate matter types, water chemistry, and flow fields (Krishnappan, 2022; Livsey et al., 2022; Maltauro et al., 2023).

Flocculation processes have been greatly overlooked in riverine environments (Lamb et al., 2020), especially in high-energy gravel-bed rivers, where flow fields are invariably turbulent. However, high-energy gravel-bed rivers draining forested mountainous landscapes are critical to downstream water supply (Emelko et al., 2011) and regional ecological integrity (Hauer et al., 2016), and catastrophic landscape events such as wildfires, which have been increasing in intensity and frequency due to ongoing climate change (Westerling et al., 2006), pose a great threat to these high-quality river systems by altering the dynamics of fine sediment transport and fate (Stone et

al., 2021b). Recent work has demonstrated the important role of flocculation (Droppo and Krishnappan, 2016; Lai et al., 2018; Lick, 1982; Lick et al., 1992; Ongley and Bynoe, 1982; Williams et al., 2008) on the transport properties of cohesive materials, even within turbulent flow fields (Izquierdo–Ayala et al., 2021; Livsey et al., 2022; Maltauro et al., 2023; Sahin et al., 2017). Moreover, studies have reported on the interactions between cohesive suspended sediment and gravel-bed channels through ingress mechanisms, which have important consequences for interstitial storage and deleterious ecological impacts caused by excess deposition and colmation (the process of interstitial clogging) (Bilotta and Brazier, 2008; Wharton et al., 2017; Wilkes et al., 2019; Wood and Armitage, 1997), and the timing for downstream propagation of fine sediment and associated contaminants (Droppo and Krishnappan, 2016; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018). Yet, much less is currently known about the effects of the gravel bed on flocculation processes and to what extent flocculation affects the interactions between cohesive sediment and gravel substrates.

Despite the turbulent flows characteristic of mountainous gravel-bed rivers, gravitational deposition due to particle settling can still occur in areas of flow separation, reverse circulation, or reaches with reduced slopes, especially during periods of low flows (Legout et al., 2018; Rathburn and Wohl, 2003; Wood and Armitage, 1997). Due to the intrinsic nature of cohesive particles, surface deposition leads deposited sediment to undergo stabilization and consolidation processes that have been observed to increase the critical flow energy required to resuspend deposited materials (Lau and Droppo, 2000). In riverine systems, the entrainment of deposited cohesive sediments, in terms of sediment concentration, has been observed through laboratory assessments to be affected by the following: the nature of cohesive particles, as stabilization can be enhanced by biochemical sediment interactions (Gerbersdorf et al., 2008); the concentration of the

suspension at the time of deposition (Tran and Strom, 2019); the antecedent conditions leading to the deposition, as particles deposited under higher flow energy are known to withstand even higher energy prior to resuspension (Lau and Droppo, 2000); the consolidation period before resuspension (Garcia-Aragon et al., 2011); and the rate in which flow energy is increased to promote bed erosion (Krishnappan, 2004). However, while some studies have reported on particle size changes of resuspended cohesive sediment (Garcia-Aragon et al., 2011; Tran and Strom, 2019), it is still not clear how flocculation and particle breakage processes affect EPSDs once deposited particles are resuspended into the turbulent flow field.

Understanding how EPSDs change as cohesive particles are transported in the flow field is critical for elucidating the transport and fate of these particles (Upadhyay et al., 2021; Williams et al., 2007). Further, given the environmental importance of gravel-bed rivers (Hauer et al., 2016), understanding cohesive sediment transport properties in these systems is of great importance for their improved management and conservation, especially given the limitation of flocculation studies in high-energy flow fields. Accordingly, the objectives of this study were to (i) evaluate EPSDs under different conditions of shear stress and bed type (plane-impermeable and plane-porous gravel bed) during erosion and deposition experiments in a rotating annular flume; (ii) examine flocculation processes through the measured EPSDs; and (iii) compare results obtained from the laboratory flume experiments with in situ measurements in the Crowsnest River.

5.3. Methods

5.3.1. Rotating Annular Flume

The rotating annular flume located in the Canada Centre for Inland Waters (CCIW—Burlington, ON, Canada) was used in this study, and the flume has been previously described in

detail along with its pictures and schematic representation (Krishnappan, 2022). The flume (30 × 30 cm cross-section) has an annular diameter of 5 m and a channel circumference of 15.7 m. The channel is covered with a lid of adjustable height that is configured to remain in contact with the water surface throughout experiments. Counter-rotation between the channel and the lid generates a nearly two-dimensional flow field with nearly uniform shear stress distribution. Such conditions enable the flume to replicate an infinite river, making it a globally unique piece of equipment for the study of flocculation and cohesive sediment transport processes (Droppo and Krishnappan, 2016; Krishnappan and Engel, 2006; Stone and Krishnappan, 2003) (See Appendix D).

5.3.2. Flume Experiments and Sampling Procedure

Deposited fine matrix sediment and framework gravel were collected from the Crowsnest River (Figure 5.1) and shipped to the flume location. Fine sediment (sieved to <63 μm) was collected from an area of reverse circulation using the method of Lambert and Walling (Lambert and Walling, 1988). Gravel bed framework (sieve-washed > 2 mm) was collected in equal proportions from four sites of the river (Figure 5.1). The gravel (in the field: $D_{10} = 15$ mm, $D_{50} = 47$ mm, $D_{90} = 140$ mm; and truncated at 40 mm in the flume: $D_{10} = 10$ mm, $D_{50} = 24$ mm, $D_{90} = 35$ mm) was used in the ingress experiments to form a coarse bed with depth of 3.2 ± 0.6 cm and average porosity of $36.2 \pm 3.8\%$.

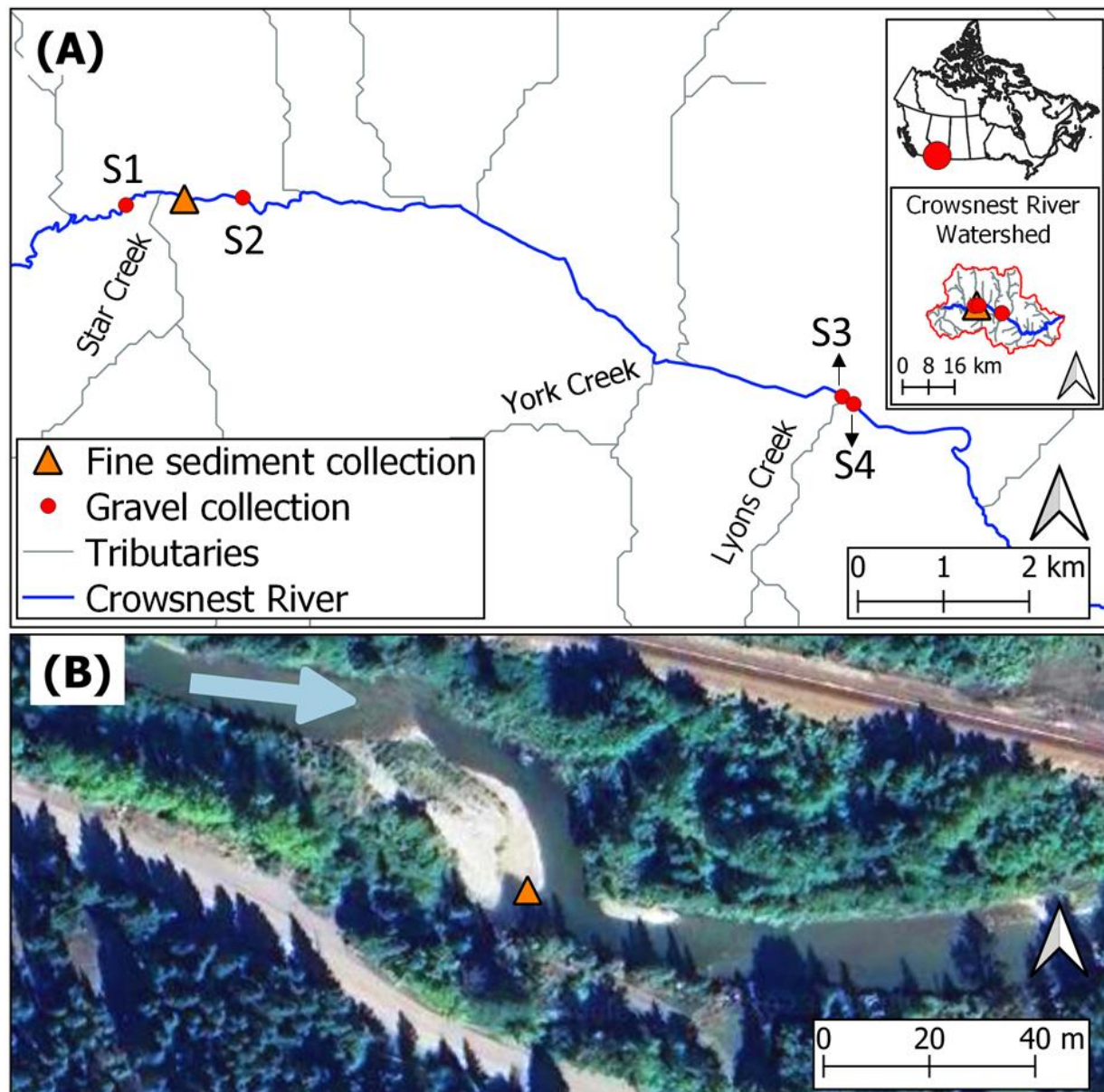


Figure 5.1. (A) Study sites, and (B) location of the collection fine sediment collection for the flume experiments.

A total of eight experiments were conducted in the flume (Table 5.1). The deposition experiments were conducted with no addition of bed gravel (impermeable flume bed). For the first deposition experiment (D1), the flume was filled with water up to a depth of 12 cm, and a fine sediment slurry was added to generate a total suspended solids (TSS) concentration of $\sim 300 \text{ mg L}^{-1}$. More slurry was added to the flume for the remaining deposition and erosion experiments to

generate a TSS concentration of $\sim 500 \text{ mg L}^{-1}$. For all deposition experiments, the flume was operated at maximum speed during the initial 20 min to keep particles in suspension. After 20 min, the rotation speed was decreased in each run to promote varying applied shear stresses (Table 5.1). For erosion experiment E7, sediment in the flume was fully resuspended and then allowed to settle for 24 h. After the 24 h consolidation period, shear stress was applied as a stepwise function to promote particle resuspension.

Table 5.1. Summary of the experimental procedure conducted in the rotating annular flume.

ID	Experiment	Initial TSS (mg L ⁻¹)	Applied Shear Stress		Bed Type	PSD Sampling Time (min)
			0 to 20 min	20 to 300 min		
D1	Deposition	273.09	0.46 Pa	0.12 Pa	Flume	20, 60, 100, 200, 300
D2	Deposition	480.41	0.46 Pa	0.00 Pa	Flume	
D3	Deposition	483.76	0.46 Pa	0.06 Pa	Flume	20, 300
D4	Deposition	476.74	0.46 Pa	0.12 Pa	Flume	
D5	Deposition	464.87	0.46 Pa	0.21 Pa	Flume	20, 60, 100, 200, 300
D6	Deposition	473.82	0.46 Pa	0.32 Pa	Flume	
I8	Ingress	171.30	0.46 Pa	0.32 Pa	Gravel	10, 20, 40, 70, 100, 130, 160, 190, 220, 250, 280, 300
E7	Erosion	3.47	0 to 580 min		Deposited sediment over the flat flume bed	0, 10, 50, 70, 110, 130, 170, 190, 230, 250, 290, 320, 390, 410, 480, 500, 570
			Stepwise increase-see Figure 5.2			

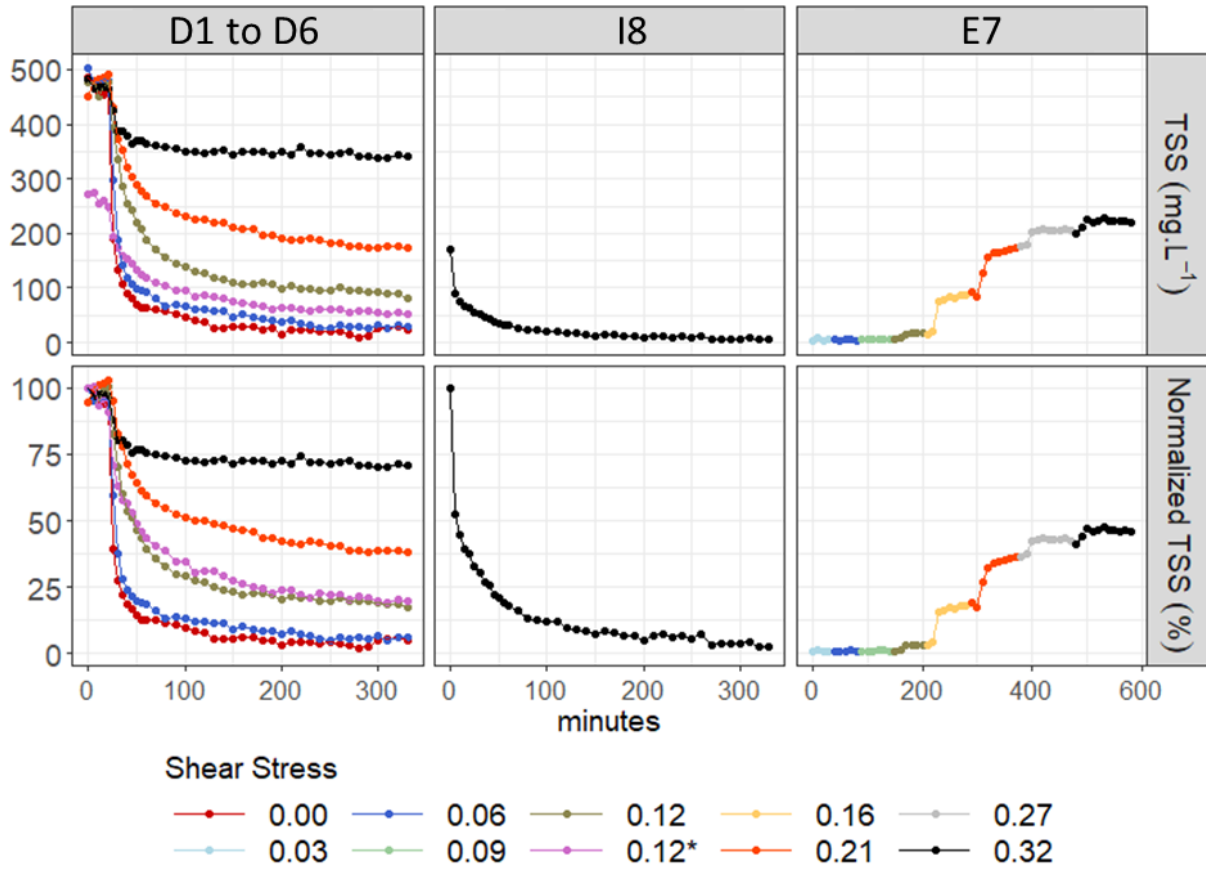


Figure 5.2. Measured and normalized TSS (TSS_n/TSS₀ for deposition and ingress, and TSS_n/TSS_{0Dep} for erosion experiments) for all flume tests. * corresponds to the measurements taken in experiment D1, when initial concentration was ~300 mg L⁻¹.

For the ingress experiment (I8), gravel was added into the flume and manually “packed” to create a plane-porous gravel bed (Krishnappan and Engel, 2006; Mooneyham and Strom, 2018). The flume was then filled with water to a depth of 16 cm, and sediment–water slurry was added to the flume through the same procedure as in the deposition experiments. In the ingress experiment, similarly to the deposition experiments, the flume was operated at the highest speed for 20 min. Then, the rotation speed was decreased to generate a shear stress of 0.32 Pa (Table 5.1).

Samples for TSS and EPSD were collected through a tube and valve installed in the wall of the flume. The inflow end of the tube faced the flow, and it sampled at a height of 6 cm from the bottom of the flume channel. Before sample collection, the valve was opened to flush still water from within the tube, and the flushed water was re-inserted into the flume to maintain constant water levels. TSS was measured following the Standard Methods Procedure (American Public Health Association (APHA), 1995). EPSDs were measured immediately after sampling with a LISST-200x (Sequoia Scientific, Bellevue, WA, USA). In all experiments, TSS was measured every 5 min for the initial 60 min and every 10 min until the end of the experiment. The timing of EPSD measurements is shown in Table 5.1. The EPSDs, measured as volume concentrations (VCs) of particles in 36 size classes, were also assessed in terms of relative EPSDs, by normalizing each size class in relation to the total VC.

5.3.3. Particle Size and Statistical Analysis

TSS measurements were normalized relative to the initial TSS for each flume run to assess particle cohesiveness. For the deposition and ingress assessments, normalized sediment concentrations were calculated as TSS_n/TSS_0 , where TSS_n corresponds to the TSS measurement taken at time n , and TSS_0 is the measurement taken at time 0. For the erosion run, normalized concentrations were calculated as TSS_n/TSS_{0Dep} , where TSS_{0Dep} corresponded to the average of initial concentrations in experiments D2 to D6 ($\sim 500 \text{ mg L}^{-1}$).

Rather than assessing flocculation through comparisons between absolute (dispersed) and effective median particle sizes (Phillips and Walling, 2005; Williams et al., 2007), flocculation was evaluated through the assessment of bimodality observed in EPSDs in all experiments. Bimodal EPSDs have been characteristically observed in suspended cohesive sediments due to the mixing

of multiple particle and floc size fractions caused by shear-dependent flocculation (Droppo et al., 1998; Lee et al., 2012; Maltauro et al., 2023; Mikkelsen et al., 2006). The bimodal evaluation was conducted by calculating a ratio (flocculation ratio) between the volume concentration of smaller (mostly constituted of primary particles and flocculi that are the building blocks of coarser flocs) and larger flocs. In all EPSDs, a minimal point between modal peaks seemed to occur at particle sizes around 9 μm , a size that was defined as a threshold for the calculation of the flocculation ratio:

$$\text{Flocculation ratio} = \frac{VC_{<9\ \mu\text{m}}}{VC_{>9\ \mu\text{m}}} \quad (1)$$

where $VC_{<9\ \mu\text{m}}$ represents the cumulative volume of flocs below 9 μm and $VC_{>9\ \mu\text{m}}$ represents the cumulative volume of flocs greater than 9 μm . Flocculation ratios were also calculated for EPSDs measured in situ in two field campaigns in the Crowsnest River. EPSDs were measured in situ at four sites on the Crowsnest River (Figure 5.1) with a LISST 200-x every ~ 4 days during the summer months of 2019 and 2021. At the same intervals, discharge values were measured at the same sites and were used in the flow model MOBED (Krishnappan, 2022) to calculate bed shear stress values.

Flocculation ratios were linearly regressed against shear stress for all flume and field measurements. All statistical analyses and graphing were performed in R Statistical Software version 4.3.2 (R Core Team, 2022) through the RStudio Integrated Development Environment (RStudio Team, 2022). Pairwise comparisons were performed using the Mann–Whitney U test (MWU) and Benjamini–Hochberg (BH) false discovery rate correction for multiple comparisons with the “rstatix” package (Kassambara, 2021). All graphs were plotted using “ggplot2” (Wickham, 2016), and linear regressions were plotted using “ggpubr” (Kassambara, 2020).

5.4. Results and Discussion

Commonly used catchment sediment budget models often disregard flocculation mechanisms in their parameterization due to the complex transport nature of cohesive particles. Cohesive sediments, however, manifest altered density and settling properties, ultimately affecting particle transport and fate (Krishnappan, 2022; Lamb et al., 2020; Livsey et al., 2022). Here, such cohesive characteristics have been observed through flume experiments.

5.4.1. Influence of Suspended Sediment Concentration on Fine Sediment Deposition

In contrast to non-cohesive fine sediments, initial suspended sediment concentrations are an important factor controlling the deposition of cohesive particles (Krishnappan, 2022; Partheniadis and Kennedy, 1966). Here, suspended sediment concentrations reached the steady state in all deposition and ingress experiments (Figure 5.2). The smallest TSS values in the steady state were observed for the deposition experiments at 0.00 Pa (D2) and 0.06 Pa (D3), and in the ingress experiment at 0.32 Pa (I8, Figure 5.2). The effects of initial suspended sediment concentration on deposition were confirmed between experiments D1 and D4, where for the same applied shear stress, a higher TSS_0 in D4 resulted in a higher steady state concentration for this experiment (D1 and D4, Figure 5.2). According to Partheniades and Kennedy (Partheniadis and Kennedy, 1966) and Krishnappan (Krishnappan, 2022), this occurs because when larger (loosely bound) settling flocs reach the near-bed, higher shear stress region, only flocs that are sufficiently strong to withstand that shear will deposit, while flocs that are less strong will break up and return to suspension as smaller flocs. This critical floc size and strength to undergo deposition are intrinsic to the nature of the studied sediment and the applied shear stress. As such, for cohesive particles,

a higher TSS_0 will not change the critical particle size for deposition, but it will increase the relative fractions of solids in each size class remaining in suspension at the steady state. Accordingly, when TSS curves are normalized as a function of TSS_0 , the deposition process becomes dependent only on the applied shear stress, thus causing normalized curves to overlap (D1 and D4, Figure 5.3B) and confirming the cohesive properties of the fine sediment investigated experimentally. The relationships described have also been observed by others (Mehta and Partheniades, 1975; Mooneyham and Strom, 2018), and demonstrate that, while the steady state concentration depends on TSS_0 , the normalized TSS concentrations are only a function of shear stress. In turn, as stated by Krishnappan (Krishnappan, 2022), the analysis of cohesive sediment transport might benefit from the utilization of normalized concentrations since they become only dependent on applied shear stress.

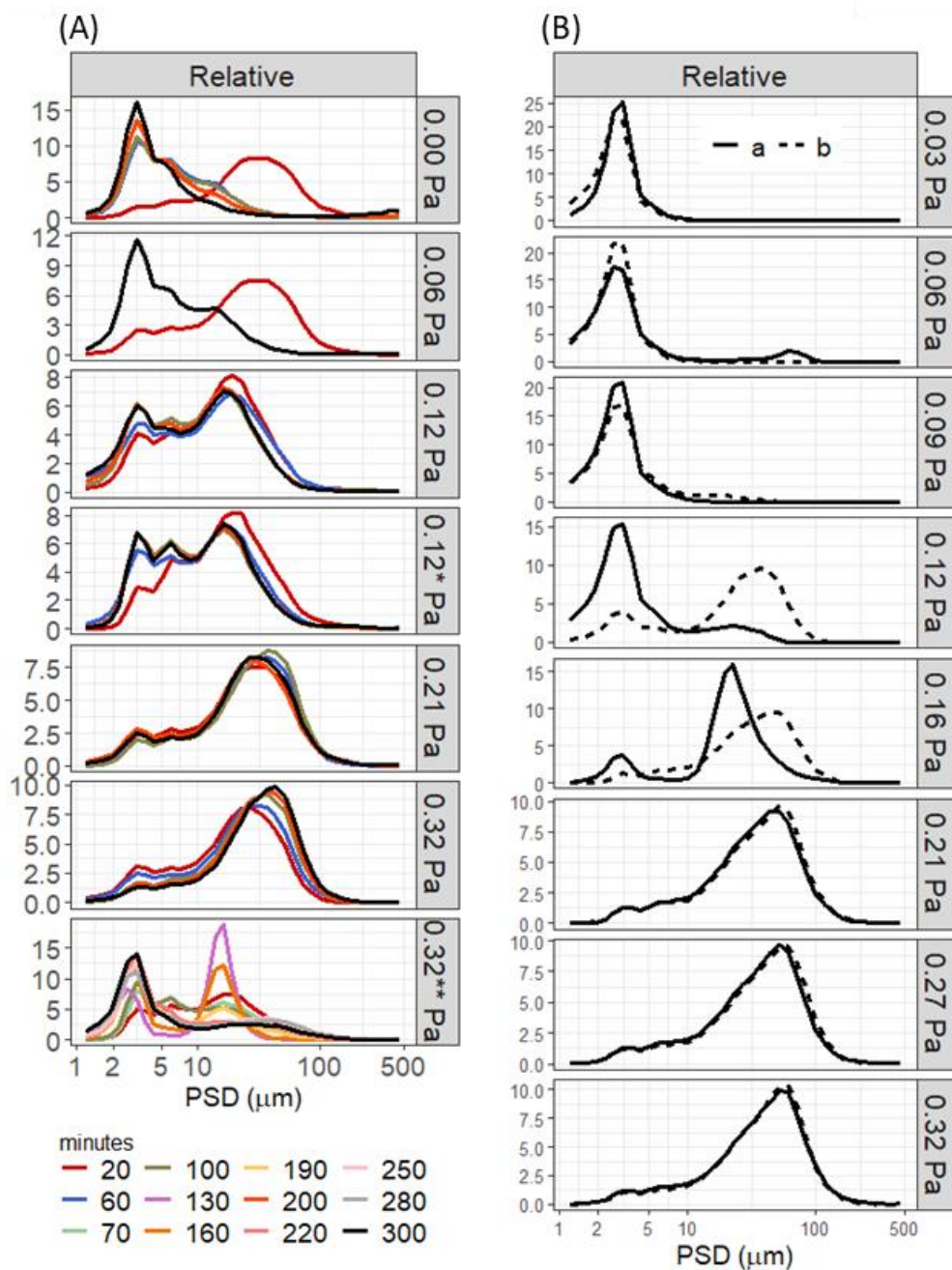


Figure 5.3. Particle size distributions by relative volumetric concentration (%) from (A) deposition and ingress, and (B) erosion experiments. In (A), D1 = 0.12 * Pa, D2 = 0.00 Pa, D3 = 0.06 Pa, D4 = 0.12 Pa, D5 = 0.21 Pa, D6 = 0.32 Pa, I8 = 0.32 ** Pa. In (B), letters a and b, respectively, represent measurements taken at 0 and 10 min at 0.03 Pa, 50 and 70 min at 0.06 Pa, 110 and 130 min at 0.09 Pa, 170 and 190 min at 0.12 Pa, 230 and 250 min at 0.16 Pa, 290 and 320 min at 0.21 Pa, 390 and 410 min at 0.27 Pa, 480 and 570 min at 0.32 Pa. * corresponds to the measurements taken, when initial concentration was $\sim 300 \text{ mg L}^{-1}$, ** corresponds to the ingress experiment.

5.4.2. Shear-Dependent Flocculation

Flocculation was consistently observed and further confirmed through photomicrographs taken during each experiment (Figure 5.4). Increasing the applied shear stress in deposition and erosion experiments (except for experiment I8—discussed below) consistently increased D_{50} and D_{90} values (Figure 5.5). The positive relationship between shear stress and particle size, within the ranges of applied shear stress of this study, has also been observed elsewhere in similar flume experiments studying cohesive sediments from different sources (Krishnappan, 2022; Stone and Krishnappan, 2003). As widely observed in flocculation studies, increasing particle size with shear stress is a response of increased particle interaction followed by flocculation (Casson and Lawler, 1990; Winterwerp, 1998). Beyond a certain threshold of flow energy that is inherent to the sediment characteristics (i.e., its primary particles, organic and inorganic solids, and strength of binding mechanisms), increasing flow energy causes excessive particle collision and/or turbulent effects, leading to floc breakage (Livsey et al., 2022; Stone and Krishnappan, 2003; Tran and Strom, 2019; Winterwerp, 1998). However, varying the shear stress affects flocculation responses differently according to floc size fractions, given the different aggregation strengths associated with each floc size class (Eisma, 1986; Lee et al., 2012; Maltauro et al., 2023; Mikkelsen et al., 2006). Accordingly, larger flocs (micro- and macro-flocs, with no commonly agreed size threshold, but reportedly $>20\text{ }\mu\text{m}$, and $>100\text{ }\mu\text{m}$, respectively) have important bonding mechanisms due to biological agents (e.g., protruding filamentous bacteria, and extracellular polymeric substances), which can result in a weaker floc strength relative to more strongly bound flocculi (floc sizes $< 20\text{ }\mu\text{m}$, approximately), which are predominantly bonded by cohesion (electrostatic and van der Waals forces) (Ho et al., 2022; Lee et al., 2012; K. L. Spencer et al., 2021).

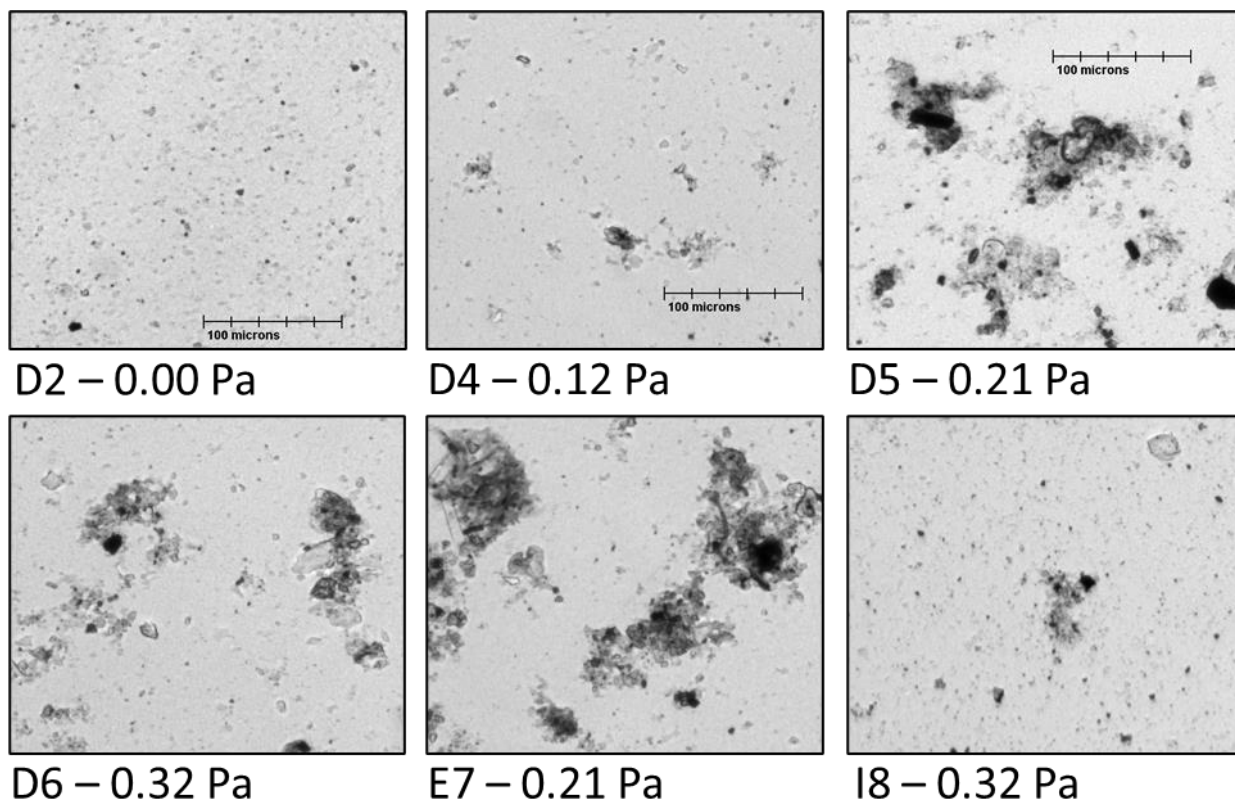


Figure 5.4. Photomicrographs of flocs from the flume experiments. All samples collected at ~ 300 min from the beginning of the experiment. All images are on the same scale.

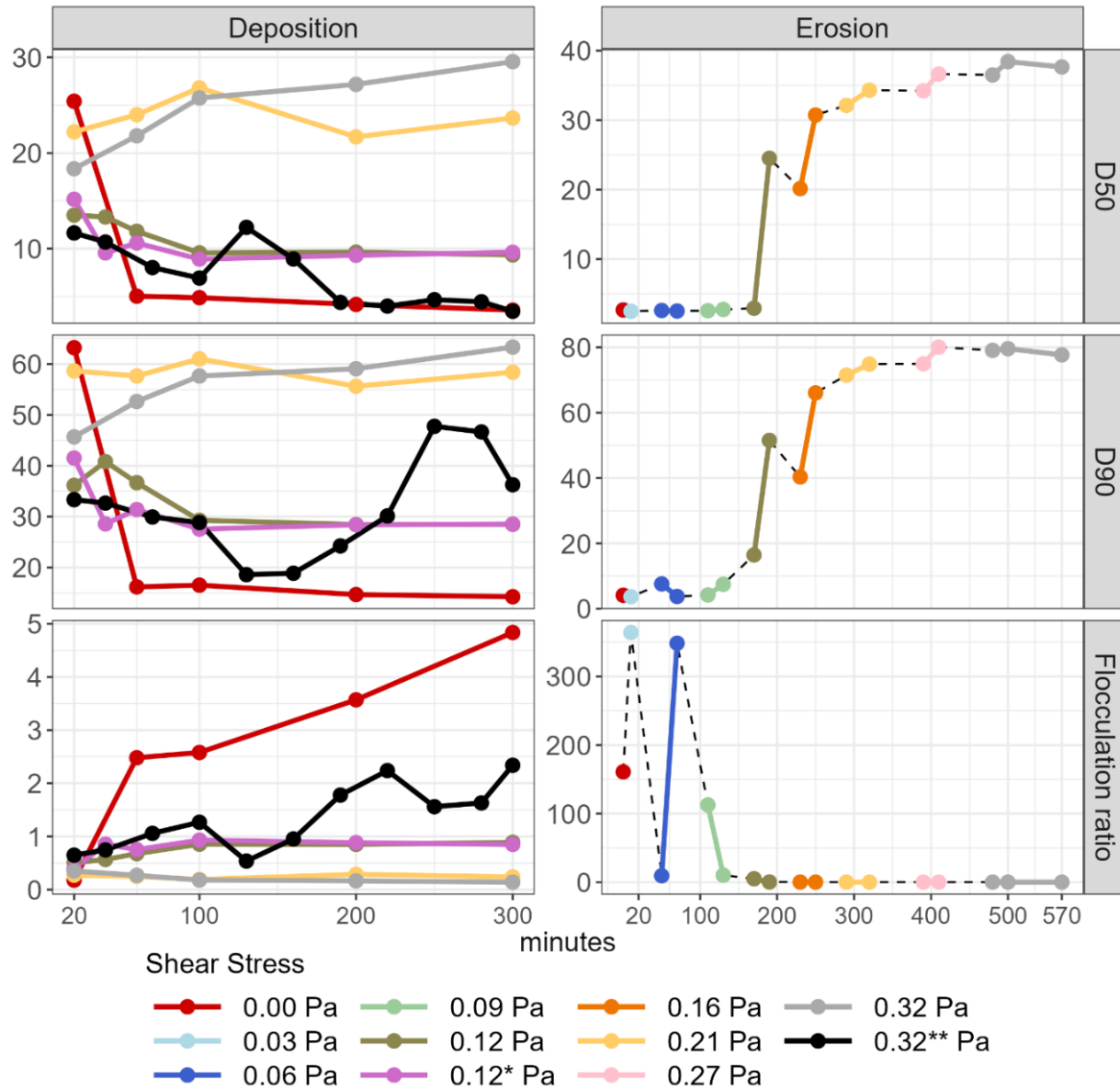


Figure 5.5. D_{50} , D_{90} (μm), and flocculation ratio ($VC_{<9\mu\text{m}}/VC_{>9\mu\text{m}}$) change over time. Deposition and ingress experiments have constant shear stress applied to flow. The erosion experiment has a stepwise increase in shear stress. * indicates experiment D1, and ** indicates experiment I8. Dashed line in the erosion experiment is shown to emphasize the observed trend between data points.

It has been widely observed that increased turbulent effects limit flocculation and decrease median particle sizes, as discussed above. Here, the linear regressions performed with EPSDs

measured in the flume experiments and in situ in previous years (2019 and 2021) showed a negative relationship between flocculation ratios and shear stress (Figure 5.6). All linear regressions were statistically significant ($p < 0.05$) except for site 3, but variance in the erosion and field models was only moderately explained, as indicated by the R^2 values (Figure 5.6). The decrease in flocculation ratios is caused by a relative reduction in the VC of primary particles and flocs $< 9 \mu\text{m}$ compared to larger flocs ($9\text{--}500 \mu\text{m}$) with increasing shear. Since suspended particles ($<500 \mu\text{m}$) were observed to be predominantly transported in flocculated form in the flume and in the field (Maltauro et al., 2023), the observed relationships between shear and ratios indicate that increasing the flow energy consistently aggregated smaller particles (primary particles and flocculi) into larger flocs in the process of shear-dependent flocculation. However, we stress that this does not indicate an indiscriminate growth in floc size with flow energy, since coarse and more loosely attached flocs undergo breakage under high shear (Maltauro et al., 2023; Mikkelsen et al., 2006). Rather, the observed low flocculation ratios demonstrate that the breakage of flocs under high shear resulted in disaggregated flocs $> 9 \mu\text{m}$, thus indicating the strength of aggregation once primary particles become flocculated. Further, since flocs formed under higher shear stresses can be more resilient to breakage (Guo et al., 2021), our observations indicate that flocs in the Crowsnest River are transported in suspension in fairly stable form.

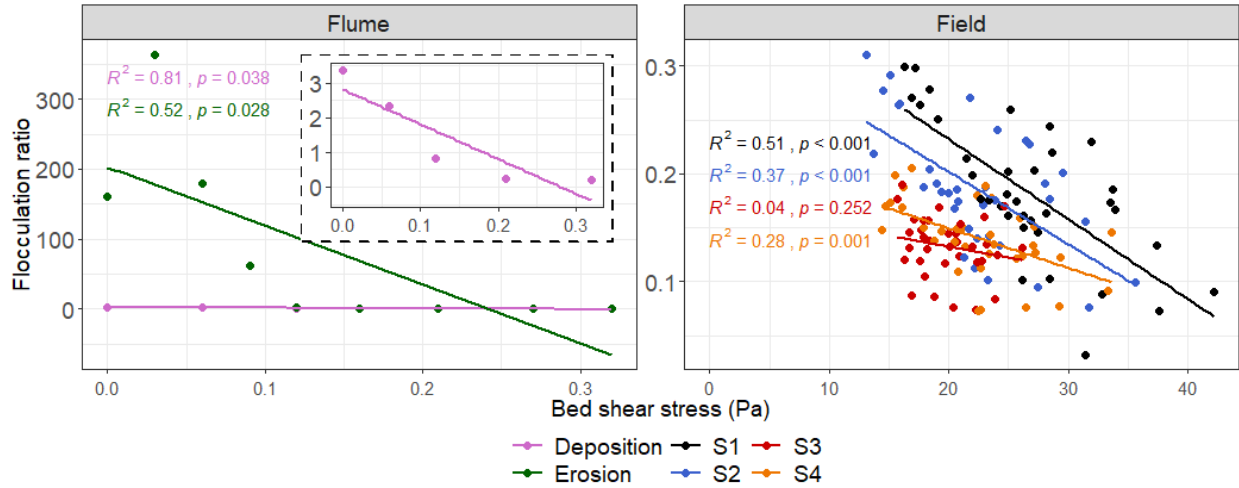


Figure 5.6. Linear regression between flocculation ratios and bed shear stress from flume and field experiments. Flume values of flocculation ratio correspond to the mean of measurements taken for the same applied shear stress at each experiment (deposition or erosion).

5.4.3. EPSDs in Deposition Experiments

Most deposition and ingress of suspended fine sediment occurred during experiments D2, D3, and I8 (Figure 5.2), and particles remaining in suspension in these experiments were predominantly $\sim 3 \mu\text{m}$ (Figure 5.3A). The EPSD observations in I8 indicate that the ingress of cohesive particles was size-selective, which is in accordance with the observations of others (Koiter et al., 2015). However, in contrast to experiments D2 and D3, in which coarser flocs had deposited after 60 min from the beginning of the experiment (Figure 5.3A), some coarser flocs remained in suspension in experiment I8 ($D_{90} \sim 45 \mu\text{m}$, Figure 5.5), and D_{90} s in I8 were statistically comparable to deposition experiments D4 and D1 (Figure 5.7).

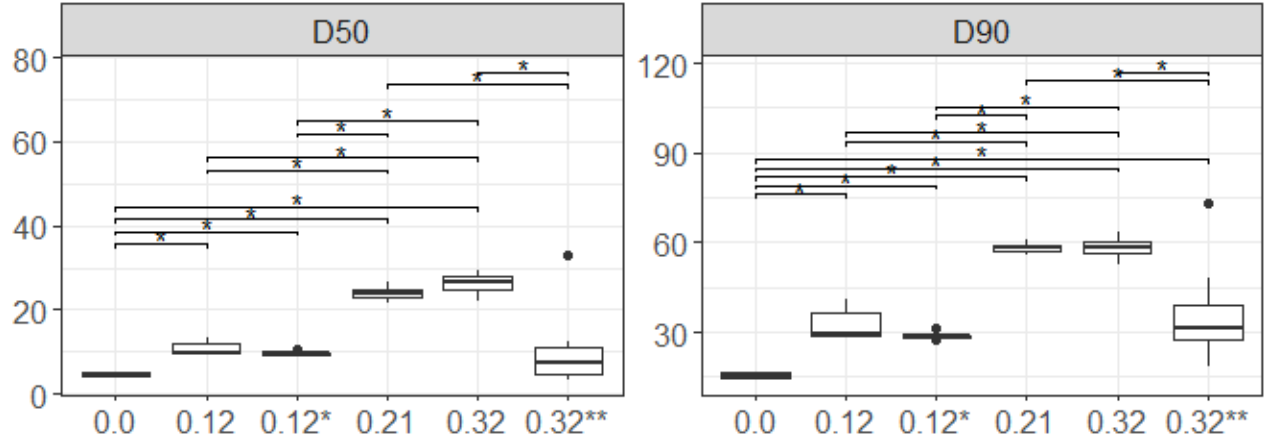


Figure 5.7. Mann–Whitney U test pairwise comparison for size (μm) measurements taken >20 min. Experiments correspond to D1 = 0.12 * Pa, D2 = 0.00 Pa, D4 = 0.12 Pa, D5 = 0.21 Pa, D6 = 0.32 Pa, I8 = 0.32 ** Pa, where $n = 4$ in 0.00 Pa, 0.21 Pa, and 0.32 Pa; $n = 5$ in 0.12 Pa and 0.12 * Pa; and $n = 12$ in 0.32 ** Pa. p -values: * $p < 0.05$. Median, upper, and lower quartiles; whiskers indicate the range spanning 1.5 times the interquartile range.

After 60 min of the experiment in all deposition runs (D1 to D6), we observed that particle size distributions approached a quasi-equilibrium state, as no systematic variation between the EPSDs under these experimental conditions was observed (Figure 5.3A), and flocculation ratios were nearly constant in experiments D1, D4, D5, and D6 (Figure 5.5). This particle size steady state has been previously observed in flocculation assessments of pure mineral clay mixtures and synthetic polymers (Spicer et al., 1998; Spicer and Pratsinis, 1996; Strom and Keyvani, 2016) and for riverine cohesive sediments (Krishnappan, 2022; Stone and Krishnappan, 2003), demonstrating an intrinsic nature of cohesive particles under steady shear stress applications. For run D2, however, which had no applied shear stress (0.00 Pa), flocculation ratios increased with time (Figure 5.5), demonstrating the continuous settling of coarser flocs relative to the smaller particles ($\sim 3 \mu\text{m}$) retained in suspension (Figure 5.3A).

The steady state of particle sizes observed in the deposition experiments has important implications from the perspectives of engineered environments and water and wastewater treatment facilities (Jarvis et al., 2005). However, the experiments over the gravel bed did not lead to a particle size steady state. Contrary to the deposition experiments, and despite the same applied shear stress between experiments D6 and I8, several modal changes in EPSDs were observed during experiment I8 (Figure 5.3A), which was further reflected in significant differences between median particle sizes (Figure 5.7). In experiment I8, measurements taken at 130 and 160 min during the experiment showed a strong and well-defined bimodality, with first and second peaks at ~ 3 and ~ 20 μm , respectively (Figure 5.3A). Measurements >160 min in I8 showed a decrease in the second modal peak (~ 20 μm) of relative EPSDs in relation to measurements <160 min (Figure 5.3A), but a flocculation steady state, such as the ones observed in the deposition experiments, was not observed, as D_{90} s and flocculation ratios varied with time (Figure 5.5). Such peculiar behavior in EPSDs in the ingress experiment was further demonstrated by flocculation ratios, which presented varying values during experiment I8 (Figure 5.5).

To the authors' knowledge, the observed EPSDs from experiment I8 have not been reported elsewhere. In a similar flume experiment, Mooneyham and Strom (Mooneyham and Strom, 2018) have reported one example of a measured EPSD from an ingress experiment, but they did not observe varying EPSDs like the ones reported herein. The non-steady particle size observations from I8 could be attributed to particle collision and flocculation processes of particles that were exfiltrating from the gravel framework, resuspending from the fine sediment deposited on top of the gravel bed, or due to particles remaining in suspension. However, in the deposition experiment (D6) with the same applied shear stress of 0.32 Pa as in I8, only 25% of the available suspended sediment had deposited onto the bed, suggesting that even less surficial deposition would have

occurred in I8 due to the likely increased near-bed shear stress caused by the gravel presence. Further, TSS measurements from experiment I8 showed that the gravel channel was very effective in ingressing suspended particles and that no significant exfiltration or resuspension occurred in this flume run (Figure 5.2), which is in accordance with other studies assessing cohesive sediment ingress over gravel-bed channels (Krishnappan and Engel, 2006; Mooneyham and Strom, 2018). Further, it has been observed that interstitial fine sediment exfiltration, without framework mobilization, is likely limited to the upper layers of the bed (Detert and Parker, 2010; Kuhnle et al., 2016; Schälchli, 1992). Therefore, we believe that if any exfiltration or resuspension had occurred in I8, it would have quickly been re-ingressed into interstitial storage, and, as the experiment progressed, interstitial fine sediment would have continued to ingress deeper in the bed, becoming increasingly less available for exfiltration (Gibson et al., 2009). Hence, it is likely that the observed transient particle size characteristics at 130 and 160 min were caused by the interaction of particles that were remaining in suspension, which consisted of ~12% and ~5% of the initially available suspended sediment (Figure 5.2), respectively, for those measurement times. Further, we believe that the coarser D_{90} s observed in I8 >160 min were also caused by the interaction of the particles remaining in suspension, which represented less than ~5% of the initially suspended sediment (Figure 5.2), but were likely interacting due to the turbulent shear. Our observations of EPSDs in I8, although limited to the single experiment conducted for the gravel bed, reflect the complexities that are added to flocculation mechanisms by the coarse channel, and demonstrate the need for future investigation of such processes.

5.4.4. EPSDs in Erosion Experiments

In the erosion experiment, similar to experiments D2, D3, and I8, particles in the $\sim 3 \mu\text{m}$ size range were predominantly in suspension at the beginning of the experiment (E7, Figure 5.3B). In E7, applied shear stresses of 0.03, 0.06, and 0.09 Pa led to no surficial resuspension (Figure 5.2), and no flocculation was observed (Figure 5.3B). For applied shear stress ≥ 0.12 Pa, however, resuspension of the bed particles started to occur (Figure 5.2), also influencing suspended sediment EPSDs (Figure 5.3B). Through the stepwise increases in shear stress, at 0.12 and 0.16 Pa, we observed that EPSD measurements taken following the incremental increase in flow energy (measurements a, Figure 5.3B) were generally finer than measurements taken once shear stress had stabilized (measurements b, Figure 5.3B), demonstrating that resuspended particles were undergoing flocculation when in suspension. Such differences between initial and final (a and b) measurements decreased when shear stresses were ≥ 0.21 Pa (Figure 5.3B), demonstrating that EPSDs were reaching an equilibrium in flocculation processes despite the increasing TSS due to bed erosion (Figure 5.2).

Changes in TSS concentrations from the erosion experiment (E7) showed that even under the highest applied shear stress of 0.32 Pa, only $\sim 50\%$ of the deposited sediment was resuspended, thus demonstrating the importance of consolidation on the fate of cohesive sediment (Figure 5.2). Our observations in E7 lead us to believe that, while flocculation was an important process for suspended floc size growth, especially at 0.12 and 0.16 Pa, the resuspension of coarser bed particles likely influenced the measured EPSDs at the end measurement of each shear stress increment (measurements b, Figure 5.3B). When comparing D_{50} s and D_{90} s of the erosion and deposition tests under the same applied shear stress (i.e., E7 at 0.12 Pa, 0.21 Pa, and 0.32 Pa with D4, D5, and D6, respectively), we observed that particles were consistently coarser in the erosion

experiment. As such, it is believed that bed material that had undergone stabilization and consolidation (Krishnappan, 2004; Lau and Droppo, 2000) resuspended as coarser flocs. In cohesive sediment deposits, consolidation (self-weighted consolidation) and biostabilization (due to microbial extracellular polymeric substances) have been observed to increase bed aggregation and stability (Gerbersdorf et al., 2008; Lau and Droppo, 2000). Consequently, floc size has been observed to be positively correlated with bed consolidation periods and biostabilization processes (Garcia-Aragon et al., 2011).

Here, coarser resuspended flocs were able to maintain their enlarged size, even during the highest applied shear stress (Figure 5.3B), which is contrary to the observations of Tran and Strom (2019) and Garcia-Aragon et al. (2011), who observed that particles would increase in size when deposited, but quickly breakdown to their “equilibrium” size according to the applied shear stress in the suspension. These observations have implications on the size selectivity of ingress processes observed here and by others (Koiter et al., 2015) and are of particular concern for the legacy effects of landscape disturbances. Our observations demonstrate that flocs deposited in areas of lower flow energy can grow in size due to consolidation effects, and once they are resuspended during higher energy flows, they can maintain coarser sizes while in suspension, which, in turn, might facilitate their re-ingress in the gravel-bed channel. In scenarios of upstream landscape disturbances, these observations suggest a tendency for the postponement of sediment flushing, driving legacy impacts (Wohl, 2015).

5.5. Conclusions

Flocculation processes depend on the sediment and water’s physical, chemical, and biological properties and the flow conditions serving as media for suspended particles. Due to its

complexity, riverine flocculation is largely disregarded in sediment budget models despite its importance in the transport and fate of fine sediment and sediment-associated nutrients and contaminants. In gravel-bed rivers, generated turbulent flows increase the complexity of flocculation and cohesive sediment transport, and very little research has been reported on such interactions. Here, we were able to identify the importance of ingress on the entrapment of cohesive sediment, and the effects that roughness-induced turbulence can impose on flocculation processes, although more assessments are required to confirm and mechanistically explain our observations regarding EPSDs in ingress experiments. Our measurements from flume and field assessments demonstrated the role of flow energy on flocculation in the Crowsnest River. Further, we observed that bed consolidation not only increased the EPSDs of resuspended particles, but that larger flocs were able to withstand the flow field without undergoing breakage. These observations demonstrate that the studied sediment is predominantly transported in flocculated form, and that, once ingressed, these particles are likely entrapped until bed mobilization. Although colmation is not a great concern in the studied gravel-bed river, given the high-energy and non-saturated channel, the observations from this study can have important consequences for the potential legacy effects that can arise from upstream landscape disturbances. Given the complexity of flocculation processes over gravel-bed channels, we strongly believe that more testing under different scenarios (different framework compositions, applied shear stresses, fine sediment sources, and sediment supply rates) is required in order to better understand such processes. Although fine sediment exfiltration was not detected in the ingress experiment, we recommend that future research explore the potential of exfiltration processes and their influence on suspended sediment EPSDs through ingress experiments using higher fine sediment feed and feed rates.

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Chapter 6. Advancing mechanistic understanding of cohesive sediment transport: integrating flume experiments, field measurements, and modelling approaches in a gravel-bed river

6.1. Summary

In Chapter 6, a fine sediment transport model (RIVFLOC) was calibrated and validated with the experiments conducted in a rotating annular flume. RIVFLOC is a semi-empirical fine sediment transport model that incorporates the processes of flocculation and ingress. For the first time in the context of existing literature, the calibrated RIVFLOC model was applied to and compared with field observations of suspended sediment concentration. While the model was not validated for field observations, its application provided important insights into the propagation and storage of fine sediment in the study gravel-bed river. Model results demonstrated the considerable interstitial storage capacity of the Crowsnest River, where approximately 60% of available suspended sediment was predicted to become stored in the channel framework along the study reach. Given the agreement between observations of fine sediment ingress based on flume and field measurements, it is believed that the model estimates are representative of the expected field conditions for interstitial accumulation. Ingressed particles were invariably coarser than suspended flocs, even though modal distributions were similar. Such particle size relationships between ingressed and suspended particles can indicate the preferential ingress of coarser flocs, as observed in Chapter 5, or that flocs are being formed within the interstitial load. These findings have important implications for legacy effects from upstream landscape disturbances on the downstream transport and fate of freshwater flocs in gravel bed rivers.

6.2. Introduction

Gravel-bed rivers draining forested headwater regions are critical for the provision of high-quality drinking water (Emelko et al., 2016, 2011) and regional ecological integrity (Hauer et al., 2016). These regions, however, have been increasingly affected by anthropogenic and climate change-exacerbated landscape disturbances (e.g., harvesting activities and wildfires) (Westerling et al., 2006) that alter hillslope erosion and sediment delivery regimes (Silins et al., 2009; Stone et al., 2021b). Such landscape disturbances can increase the potential for sediment and sediment-associated downstream propagation of nutrients and contaminants, given the cohesive properties of such mobilized sediment (Horowitz and Elrick, 1987; Stone and English, 1993). In turn, cohesive sediments (organic and inorganic particles $<63 \mu\text{m}$), which develop colloidal and cohesive properties due to their large particle surface area (Partheniades, 2009), also undergo flocculation within the flow field, which alters their transport properties compared with primary particles, ultimately affecting their dispersal and fate (Droppo et al., 1997; Ho et al., 2022; Partheniadis and Kennedy, 1966). The associated transport of pollutants with fine particles can exacerbate deleterious impacts on river health (Bilotta and Brazier, 2008; Chapman et al., 2014; Kemp et al., 2011; Owens et al., 2005; Wilkes et al., 2019; Wood and Armitage, 1997). Despite extensive investigation on flocculation in freshwater, coastal, and engineered environments (Droppo et al., 2005a), the complexity of flocculation processes still poses a significant challenge to the modelling of cohesive sediment transport in riverine systems (Livsey et al., 2022). Accordingly, advancing knowledge on the mechanisms of cohesive sediment transport and fate warrants further attention, given the potential deleterious impacts of cohesive sediments.

Flocculation, given its effects on floc density, porosity, and size, has been observed to increase the settling velocity of particles (relative to primary particles) by one to two orders of

magnitude (Krishnappan, 2022; Lamb et al., 2020; Livsey et al., 2022). Accordingly, flocculation considerably increases the critical flow conditions required for the settling of flocs, facilitating their deposition by gravity (Krishnappan, 2007). In mountainous gravel-bed rivers, however, the high-flow energy generally exceeds the critical shear stress conditions required for deposition. Yet, fine sediments (cohesive and non-cohesive <2 mm) are consistently observed within the gravel-bed framework of these river systems due to ingress mechanisms promoted by the turbulent flow field (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Missot et al., 2021; Mooneyham and Strom, 2018). Ingress, also known elsewhere as entrapment (Krishnappan and Engel, 2006), infiltration (Frostick et al., 1984; Sear, 1993), intrusion (Beschta and Jackson, 1979), or depth filtration (Brunke, 1999), occurs when fine sediments infiltrate the framework interstices. While ingress can occur due to the infiltration of surficial sediment deposits (formed due to gravitational deposition under low flow energy) (Brunke, 1999; Wharton et al., 2017), ingress can also occur under high flow energy. Ingress during high energy flows occurs due to advective transport and/or turbulent diffusion as a consequence of the pressure gradients and turbulence effects caused by the gravel-bed and the roughness it imposes to the overlying flow field (Packman et al., 2004; Reidenbach et al., 2010; Tonina and Buffington, 2009, 2007). Although ingress processes have been relatively more studied in the case of the infiltration of surficial deposits, the mechanistic understanding of ingress during turbulent flows and the effects of flocculation under such conditions are still very limited.

When deposited or ingressing particles are prevented from migrating vertically into the gravel interstices, interstitial clogging can occur through a process denoted elsewhere as colmation (Wharton et al., 2017). In turn, cohesive sediment deposits can undergo consolidation (due to self-weight and dewatering processes) (Droppo et al., 2015; Droppo and Amos, 2001) and

biostabilization (due to the gluing effect of microbial extracellular polymeric substances) (Gerbersdorf et al., 2008), processes that are known to increase the critical conditions required to promote their entrainment. Likewise, interstitial cohesive sediment has been observed to increase the gravel framework stability using both flume (Perret et al., 2018) and field (Barzilai et al., 2013) experiments. In gravel-bed rivers, channel bed-stored fine sediment has been observed to be predominantly flushed in infrequent high-energy flows that have sufficient capacity to entrain the armour layer (Schälchli, 1992). Because of the described dynamics, ingress mechanisms in mountainous gravel-bed rivers have an important control over the retention time of interstitial fine sediment, leading to potential legacy effects from upstream landscape disturbances. Ingress of cohesive sediment has been predominantly assessed through flume studies (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018), and more investigations *in-situ* are necessary to improve understanding of such processes, which is required to further develop and refine existing cohesive transport models.

Sediment transport and catchment sediment budget models are important watershed management tools. Given the complexity of flocculation and cohesive sediment ingress processes, most available models disregard such mechanisms, increasing the potential for misrepresenting fine sediment dispersal and fate and, thereby, the effects and timing of their impacts (Stone et al., 2021b). Most fine sediment transport models assume ingress is driven through the infiltration of surficial deposits, disregarding the fine sediment ingress promoted by advective transport and/or turbulent diffusion during high energy flows. Further, most existing models disregard the effects of flocculation on the transport and ingress of cohesive particles. In contrast, RIVFLOC (Krishnappan, 1991) presents a distinguishable modelling approach for cohesive sediment transport by simultaneously considering the effects of flocculation and ingress mechanisms in

turbulent flow fields in its parameterization. The specific objectives of this study were to: i) calibrate the semi-empirical model RIVFLOC using the observations from laboratory flume experiments; ii) estimate the intra-gravel storage capacity for cohesive sediment with the calibrated model using a rigorous field dataset collected in two campaigns in 2019 and 2021 in the Crowsnest River, Canada and; iii) investigate cohesive sediment transport mechanisms controlling fine sediment transport dynamics in this gravel-bed river, identifying key knowledge gaps and potential areas for future targeted research based on observed differences between modelled and measured datasets. In this study, a rotating annular flume provided controlled conditions for the assessment of flocculation processes that are otherwise disrupted in recirculating flumes. Further, flume experiments allowed the empirical derivation of transport parameters that are required to calibrate and validate the RIVFLOC model. This is the first time that RIVFLOC has been applied to a comprehensive field dataset over a range of flow conditions, and these novel observations advance our understanding of some fundamental mechanisms affecting the transport and fate of cohesive sediment in this mountainous gravel-bed river.

6.3. Methods

6.3.1. Study site

The Crowsnest River, located on the eastern slopes of the Rocky Mountains in southwestern Alberta, flows eastward 65 km through the municipality of the Crowsnest Pass, from the Crowsnest Lake (1357 m.a.s.l.) to the Oldman Reservoir (1113 m.a.s.l.). Its tributaries originate in upper montane snowmelt-dominated regions, draining an area of 679 km². Groundwater discharge into the Crowsnest River plays an important role in controlling baseflows (Spencer et al., 2021; Wagner et al., 2014; Waterline, 2013), while peak flows are mostly controlled by snowmelt and rain-on-snow events during spring and summer months (Stone et al., 2014). Landscape

disturbances from anthropogenic (e.g., agricultural, industrial, urbanization) and climate change-related sources (e.g., wildfire) have altered ~25% of the catchment cover, with land alteration pressures increasing in the downstream direction of the river (Watt et al., 2021). In 2003, the Lost Creek Wildfire, one of the most severe wildfires to occur in the region, burned 21,000 ha of nearly contiguous forest land, leading to significant impacts on sediment delivery regimes (Silins et al., 2009). Such land alterations have resulted in legacy impacts in the region, such as changes in sediment and associated pollutant (contaminants and nutrients) export, ecological status, and stream productivity (Emelko et al., 2011; Martens et al., 2019; Silins et al., 2014, 2008; Stone et al., 2021b, 2014; Watt et al., 2021). The study reaches of the Crowsnest River are oligotrophic (Watt et al., 2021), generally presenting high water quality, except during infrequent extreme precipitation and flood events (Oldman Watershed Council, 2010).

6.3.2. Experimental procedure in the rotating annular flume

Flume experiments were conducted in a rotating annular flume (5 m diameter, 0.3 x 0.3 m channel) located in the Canada Center for Inland Waters (CCIW – Burlington, ON). The flume is a globally unique, state-of-the-art equipment that replicates an infinite river through its annular rotating channel. Unlike rectangular flumes, which can disrupt flocculation processes during flow recirculation, the annular flume allows precise assessments of flocculation processes of cohesive sediment without potential floc breakage. In the flume, a lid of adjustable height was kept in contact with the water surface throughout the experiment, and the counter rotation between the lid and channel led to the generation of a nearly two-dimensional flow with uniform shear stress distribution (Krishnappan, 1993; Petersen and Krishnappan, 1994). In all experiments, Total Suspended Solids (TSS) were measured at intervals of 5 to 10 minutes, following the Standard

Methods Procedure (APHA, 1995). Additionally, effective particle size distributions (EPSDs) of the suspended particles were measured at 20 and 300 minutes in the deposition and ingress experiments using a LISST-200x (Sequoia Scientific, Bellevue, WA, USA) calibrated to measure at a fixed sample rate mode at a 1 Hz rate (32 measurements averaged per second). Since the lidded channel design of the flume prevents direct measurements with the LISST-200x, samples from the flume were analyzed using the LISST's small-volume test chamber. To minimize potential effects of particle deposition within the test chamber, and after visually confirming that deposition effects were minimal, only the initial 40 seconds of measurements were used for assessments. The EPSD for each sampling was defined as the median of measurements ($n = 40$). Measurements of TSS and EPSD were conducted immediately following sample collection. Samples were collected from the flume through a tube and valve located in the wall of the flume, where the inflow end of the tube faced the flow at a height of 6 cm from the flume bed. The valve was flushed before each sampling to ensure that samples were representative of the actual flow conditions in the flume. A detailed description of the flume design can be found in Krishnappan (2007, 2004, 1993) and Krishnappan and Engel (2006, 2004), and its application in other studies are further described in the following papers (e.g., Droppo and Krishnappan, 2016; Krishnappan and Engel, 2006; Milburn and Krishnappan, 2003; Stone and Krishnappan, 2003).

Six flume experiments (four deposition - D1 to D4, one erosion - E5, and one ingress - I6) were conducted to calibrate the empirical model used in this study (Table 6.1) to obtain the critical shear stresses for deposition (τ_{CD}) and erosion (τ_{CE}), and the ingress parameter. For experiment D1, the flume was filled with tap water to a water depth of 12 cm, and a cohesive sediment slurry (collected from the field, described below) was added while the flume was rotating at maximum speed (leading to a bed shear stress of 0.46 Pa) to generate initial TSS concentrations of ~500 mg

L⁻¹ (Table 6.1). The sediment-water mixture produced in experiment D1 was also used for experiments D2, D3, D4, and E5, where, prior to experiments, cohesive sediment was resuspended and dispersed (manually and mechanically, with a mixer), and the flume was rotated at maximum speed for 20 minutes to provide the same initial conditions for all experiments. The flume rotation was then adjusted according to each deposition experiment to provide a determined continuous shear stress (Table 6.1). For the erosion experiment, E5, after maximum rotation and sediment dispersion, the sediment was allowed to settle for 24 hours under no flume rotation. After the settling period in E5, shear stress in the flume was increased incrementally to promote particle resuspension (Table 6.1). For the ingress experiment, gravel was placed in the empty flume to a bed depth of 3.2 ± 0.6 cm and patted down manually to provide a plane gravel-bed. In I6, tap water was used to fill the flume to a depth of 16 cm, and a cohesive sediment slurry was added to the flume at maximum flume rotation, as in D1 (Table 6.1). Applied shear stress in the ingress experiment was the same as the deposition experiment D4 in order to assess the ingress properties of the cohesive sediment (Table 6.1). Ingress rate ($\text{kg day}^{-1} \text{ m}^{-2}$) in the flume was measured in I6 as the mass of ingressed cohesive sediment (difference between initial and steady-state TSS relative to the volume of water in the flume) relative to the time in which steady state was achieved (150 minutes) and the surficial area of accumulation available to ingress (flume top cross-sectional area 4.71 m^2).

Table 6.1. Summary of the field data regarding observed flow conditions and channel bed framework, and flume conditions regarding different experimental conditions and the channel bed framework in the ingress experiment.

Field data			Flume data						
Discharge (m³ s⁻¹)			Experiment						
Annual Maxima (since 1950)			ID		Bed material	Initial TSS (mg L⁻¹)	Applied shear stress		
10% exceedance		58.1	Deposition	D1	Flume	480.41	0.00 Pa - 20 to 300 min		
50 % exceedance		28.6		D2		483.76	0.06 Pa - 20 to 300 min		
90% exceedance		13.6		D3		476.74	0.12 Pa - 20 to 300 min		
mean		32.7		D4		473.83	0.32 Pa - 20 to 300 min		
Field season data									
2019	range	3.3 - 13.3	Erosion	E5	Deposited fine sediment from D4	(stepwise increase in shear stress)			
	mean	6.2				3.47	0.03 Pa - 0 to 30 min		
	median	5.7					0.06 Pa - 40 to 80 min		
2021	range	2.2 - 11.1					0.09 Pa - 90 to 140 min		
	mean	5.15					0.12 Pa - 150 to 200 min		
	median	4.9					0.16 Pa - 210 to 280 min		
Bed shear stress (Pa)									0.21 Pa - 290 to 370 min
2019	range	16.2 - 42.2							0.27 Pa - 380 to 470 min
	mean	25.1							0.32 Pa - 480 to 580 min
	median	24.3							
2021	range	13.1 - 26.3	Ingress	I6	Gravel	171.30	0.32 Pa - 20 to 300 min		
	mean	19.6							
	median	19.6							
Channel framework			Channel framework during experiment I6						
D ₁₀ (mm)		15	D ₁₀ (mm)		10				
D ₅₀ (mm)		47	D ₅₀ (mm)		24				
D ₉₀ (mm)		140	D ₉₀ (mm)		35				
Porosity (%)		36.2 ± 3.8	Depth (cm)		3.2 ± 0.6				
Average slope (m m⁻¹ – 10 km reach)		0.0041							

6.3.3. Field assessments and sediment collection

Field assessments used for model comparison in this study were conducted at four sites of the Crowsnest River (Figure 6.1) through two field seasons performed in the summer months of

2019 and 2021. Detailed evaluation of field data and description of data collection can be found in Maltauro et al. (2023) and Maltauro et al. (2024c). For completeness, at each of the four sites, measurements of TSS, EPSDs, and flow discharge were collected every ~4 days. Values of TSS were measured following the Standard Methods Procedure (APHA, 1995). The EPSDs were measured with a LISST-200x (Sequoia Scientific, Bellevue, WA, USA). Flow discharges were measured with a FlowTracker2 (SonTek, Yellow Springs, OR, USA). Further, in 2020, a detailed topographic survey was conducted, measuring bed channel elevation every ~20 m and channel cross-sectional geometry every ~500 m along 10 km of the Crowsnest River from upstream of site 1 to downstream of site 4 (Figure 6.1). In the field, ingress rates ($\text{kg m}^{-2} \text{ day}^{-1}$) were assessed at the four sites of the Crowsnest River in seven deployment cycles (lasting from 2 to 10 days each) by using retrievable sediment trap samplers. Traps consisted of plastic containers with permeable walls (perforated with 1 cm diameter holes, 20 holes per trap) and impermeable bottoms, with an open top surface (102.6 cm^2), and were deployed in triplicate at each site during each deployment ($n = 84$). Here, we assessed ingress rates in terms of mass accumulation per area and time ($\text{kg m}^{-2} \text{ day}^{-1}$) to make them comparable to rates measured in the flume. However, we note that this calculation can slightly overestimate ingress rates since it does not account for the lateral accumulation area. The utilization of sediment traps with impermeable walls, however, can lead to a more substantial underestimation of ingress rates, given the importance of horizontal accumulation for flocculated particles (Maltauro et al., 2024b, 2024a), thereby justifying our choice of sampler design. To compare ingress from the field and flume measurements, field values of ingress rates were assessed only in terms of the finer fraction of matrix sediment ($<500 \text{ }\mu\text{m}$, flocculated size). For the flume experiments, deposited sediment (sieved to $<63 \text{ }\mu\text{m}$) and framework gravel (sieve-washed $>2 \text{ mm}$) samples were collected from the Crowsnest River

(Figure 6.1) and shipped to the location of the flume. Deposited fine sediment was collected from an area of reverse circulation in the river following the method of Lambert and Walling (1988), which consists of the collection of manually resuspended fine sediment bed deposits using a portable stilling well to minimize the loss of resuspended material by winnowing. Gravel was collected from the four study sites to produce the gravel-bed for experiment I6 (Table 6.1).

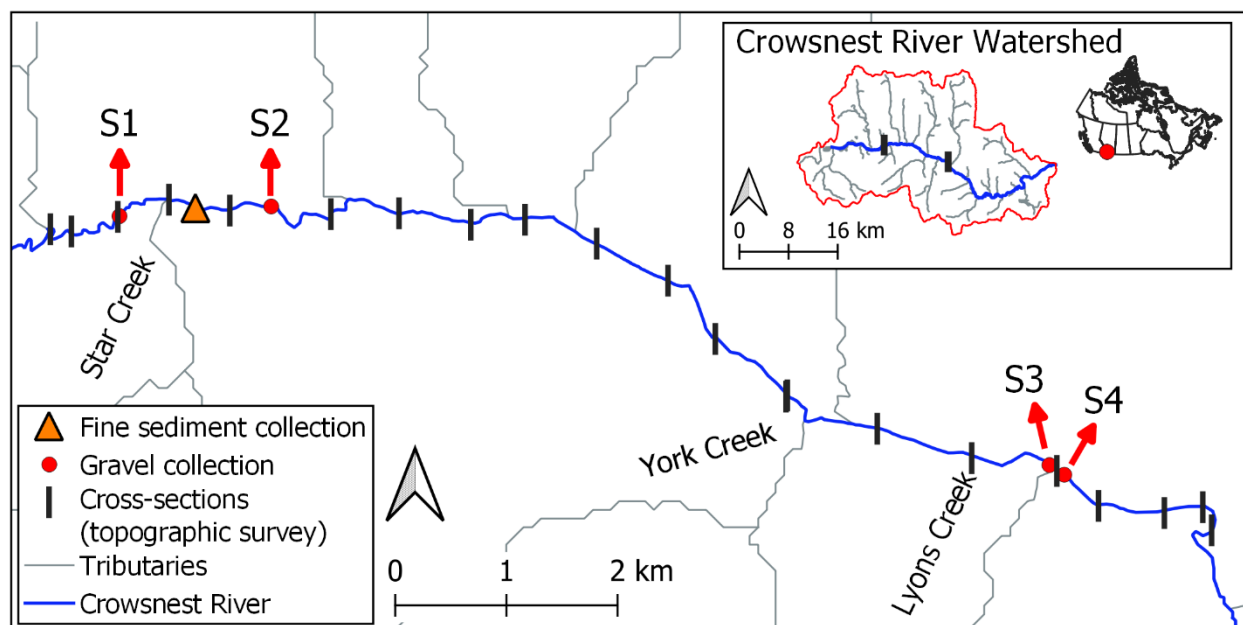


Figure 6.1. Location of the study sites in the Crowsnest River.

6.3.4. Model calibration

RIVFLOC (Krishnappan, 1991) is a semi-empirical cohesive sediment transport model that calculates the dispersion and flocculation of fine-grained sediment in river systems. While RIVFLOC can perform two-dimensional calculations, this study utilized the model in a one-dimensional modelling framework. A detailed model description can be found in Krishnappan

(1991), and its governing equations have been theoretically demonstrated previously (Krishnappan, 2022, 2007, 1991; Krishnappan and Engel, 2006). Previous studies using RIVFLOC include Droppo and Krishnappan (2016), Krishnappan (2022), Krishnappan et al. (2020), and Stone et al. (2021b). Here, for the sake of brevity, we only present the ancillary equations that have been applied in the calibration process of the model. Equations that describe the computational principal of RIVFLOC can also be found in Appendix E.

The model consists of a transport component that accounts for advective-diffusive transport and mixing of cohesive sediment and a flocculation component that accounts for collision mechanisms between particles along the river flow (Droppo and Krishnappan, 2016). The equations governing the transport component of RIVFLOC (Eq. E1 – E4, Appendix E) depend on the sediment exchange at the sediment-water interface, consisting of erosional, depositional, and ingressing fluxes at the channel bed boundary (Krishnappan and Engel, 2006). Given that cohesive sediments do not undergo erosion and deposition simultaneously, erosive fluxes were assumed to be zero in the model application (Krishnappan and Marsalek, 2002a). Such fluxes are modelled based on parameters such as floc density (ρ_f), settling velocity (ω_k), and settling probability (P) of each floc size fraction. Additional empirical parameters encompass critical shear stresses for deposition (according to the definition of Krone (1962) – τ_{CrDK} , defined as the shear stress above which none of the initially suspended particles would deposit; and the definition of Mehta & Partheniades (1975) – τ_{CrDP} , defined as the shear stress below which all the initially suspended particles would deposit) and for erosion (τ_{CrE} , defined as the critical shear stress required to initiate entrainment), plus an ingress coefficient (α). The equations governing the flocculation component of RIVFLOC (Eq. E5 – E11, Appendix E) models particle interaction through Brownian motion, turbulent shear, particle inertia, and differential settling (Krishnappan, 1991). In the flocculation

component, the flocculation collision efficiency is determined empirically through the cohesion factor (β), and the effects of turbulence on limiting particle growth is based on a methodology proposed by Tambo & Watanabe (1979).

The empirical parameters required for the calibration of RIVFLOC were obtained through the conducted flume experiments and the application of the FLUME model (Krishnappan and Marsalek, 2002b). The FLUME model is an adaptation of RIVFLOC, wherein channel geometry is adjusted for the flume settings. To calibrate the models, floc density was calculated through an empirical relationship proposed by Lau and Krishnappan (1997):

$$\rho_f = \rho + (\rho_p - \rho) \exp(-bD_k^c) \quad (1)$$

where ρ and ρ_p are the density of the water and mineral parent material, respectively, D_k is the diameter of the flocs in size class k , and b and c are empirical coefficients. Settling velocities are calculated using an adaptation of Stoke's Law as follows:

$$\omega_k = \left(\frac{1.65}{18}\right) \left(\frac{gD_k^2}{\nu}\right) \exp(-bD_k^c) \quad (2)$$

where g is the gravitational acceleration, and ν is the kinematic viscosity of water. Here, results from experiment D1 were used to calibrate, and experiments D2 to D4 were used to validate the FLUME model. Experiment D1 was chosen for the calibration because the applied τ of 0.0 Pa leads to the probability of floc deposition (P), which is calculated as:

$$P = \left(1 - \frac{\tau}{\tau_{CrDK}}\right) \quad (3)$$

to assume the value of 1, thereby simplifying the calibration process.

A linear relationship between the steady-state TSS concentrations achieved in each deposition experiment and their corresponding applied shear stresses was used to determine τ_{CrDP}

and τ_{CrDK} (Milburn and Krishnappan, 2003). The τ_{CrE} was obtained with the erosion experiment E5 and was defined as the applied shear stress leading to the bulk resuspension of the deposited fine sediment. In the calibration process of the FLUME model, parameters b , c , and β were adjusted until predicted TSS and EPSDs were comparable to the measured values in D1. Empirical parameters b , c , and β were then applied to the remaining flume runs (D2, to D4) for the FLUME model validation (Figure 6.2), and validation was concluded when all curves of TSS and EPSDs from experiments D1 to D4 were in agreement (Figure 6.3). The ingress parameter α was determined using the results from experiment I6, where α was adjusted until modelled and measured values of TSS and EPSDs in I6 presented a good agreement (Figure 6.3).

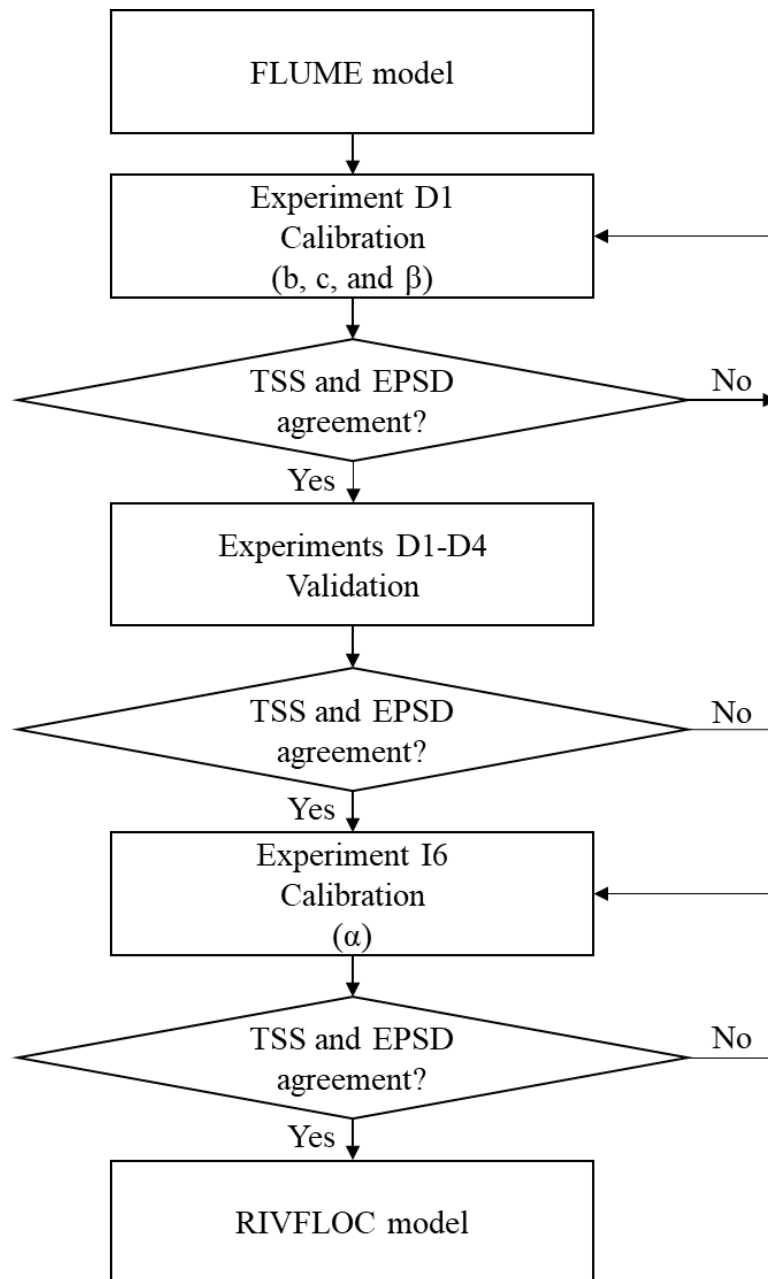


Figure 6.2. Flow chart of the model calibration process.

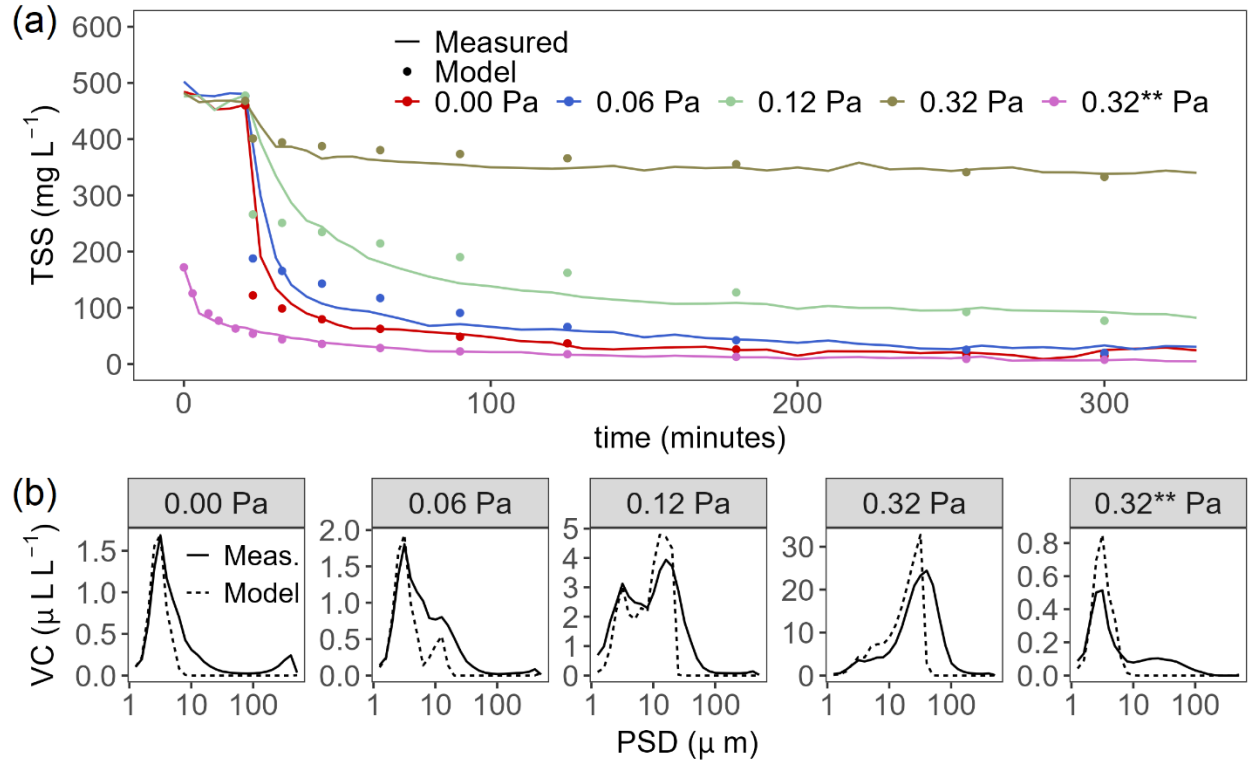


Figure 6.3. Modelled and measured values of suspended sediment concentration (a), and EPSDs (b) obtained with the FLUME model and the deposition experiments. **Ingress experiment

Empirically obtained parameters were then applied to the RIVFLOC model. In RIVFLOC, cross-sectional channel geometry (measured *in-situ* through a topographic survey, discussed above) was used for the calculations. *In-situ* measurements of TSS and EPSDs taken at site 1 were used as inputs to RIVFLOC, along with channel cross-sectional geometry, to calculate TSS and EPSD at sites 2, 3, and 4 (Figure 6.1). Discharge and bed shear stress measurements in the upstream boundary are also required for the modelling. While discharge values were measured *in-situ*, bed shear stress values were calculated with the one-dimensional flow model MOBED (Krishnappan, 1986, 1983, 1981). In MOBED, bed shear stress was derived based on field measurements of discharge, water level, and cross-sectional geometry (topographic survey), and was calculated

using Manning's relationships to obtain friction factors (full description of the calibration procedure of the MOBED model for Crowsnest River can be found in Maltauro et al. (2024c)). Accordingly, the RIVFLOC model was applied to seven different flow conditions measured *in-situ* during 2019 and 2021, varying from 2.7 to 10.5 m³ s⁻¹.

6.4. Results

The results from the flume experiments allowed the determination of critical shear stresses for deposition and erosion, and the TSS and EPSDs curves required to calibrate and validate the utilized model. The erosion experiment showed that no resuspension of surficial bed deposits occurred until an applied shear stress of 0.12 Pa, shear stress under which a small increase in TSS concentrations (denoted Type 1A erosion) was observed (Figure 6.4). The bulk of sediment erosion (denoted Type 1B erosion) started to occur at 0.16 Pa, which was defined as the τ_{CrE} , and which entrained an extra ~15% of deposited sediment (Figure 6.4B). In all deposition runs, TSS concentrations decreased initially with time, reaching a steady state concentration at ~50 min during the experiment (D1 to D4, Figure 6.3A). In deposition experiments D1 and D2, conducted under an applied shear stress of 0.00 and 0.06 Pa, respectively, only ~6% of initially available sediment remained in suspension at steady state. Increasing applied shear stress also increased steady-state concentrations, leading to ~25% and ~75% of the initially suspended TSS remaining in suspension in experiments D3 (0.12 Pa) and D4 (0.32 Pa), respectively (Figure 6.3A). Accordingly, τ_{CrDP} was determined to be slightly below 0.06 Pa, while τ_{CrDK} was determined to be 0.5 Pa. The steady-state TSS concentration in experiment I6 was much lower than for the deposition run under the same applied shear of 0.32 Pa (D4) but it was comparable to the one for experiments D1 and D2, where less than ~5% of the initially suspended sediment remained in

suspension (Figure 6.3A). This low suspended sediment concentration in I6 occurred due to the interstitial ingress of suspended sediment, and no surficial deposition on top of the gravel-bed framework was observed in the ingress experiment. Ingress rate in the flume was measured as $0.20 \text{ kg m}^{-2} \text{ day}^{-1}$, which was approximately the same as the mean recorded value of ingress rates measured in the field (Figure 6.5A). Since ingress rate measured in the flume showed good agreement with measurements taken in the field, the α coefficient was deemed reasonable for the model application. Accordingly, the best model fit was achieved when $b = 0.02$, $c = 1.0$, $\beta = 0.01$, and $\alpha = 0.2$. Factors b and c allowed the calculation of flocc density and settling velocities as a function of particle size (Figure 6.6). The application of the RIVFLOC model estimated that an average of $64.4 \pm 1.2 \%$ ($n = 7$) of the suspended sediment available upstream would ingress between the first and last assessed cross-sections (Figure 6.7). Differences between modelled and measured EPSDs (Figure 6.8) reflect the size selective deposition and ingress of particles under the highest settling velocities (Figure 6.6).

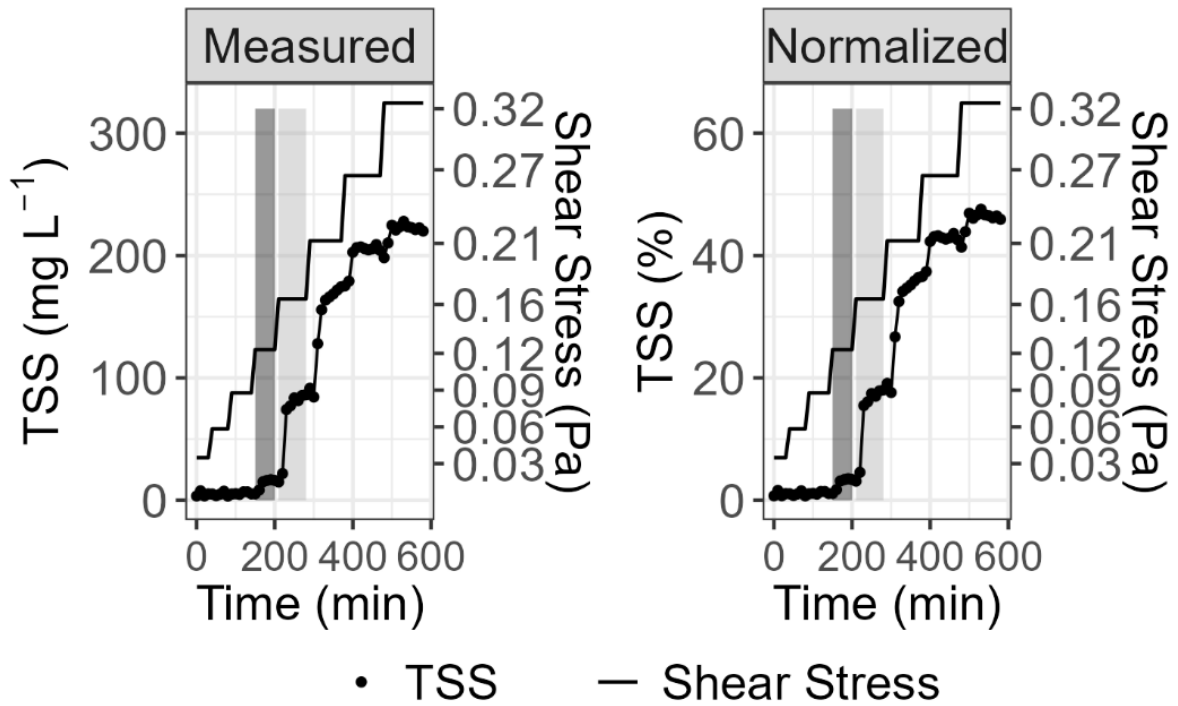


Figure 6.4. Measurements of suspended sediment concentration from the erosion experiment presented as absolute (a) and normalized (b) values of TSS. The normalization of TSS was defined as the ratio of the TSS concentration measured through experiment E5 relative to the initial TSS concentration in experiment D4, which was allowed to settle prior to E5 (normalization = $TSS_{\text{measured-E5}}/TSS_{\text{initial-D4}}$). Darker and lighter shaded areas represent Type 1A and Type 1B erosion, respectively.

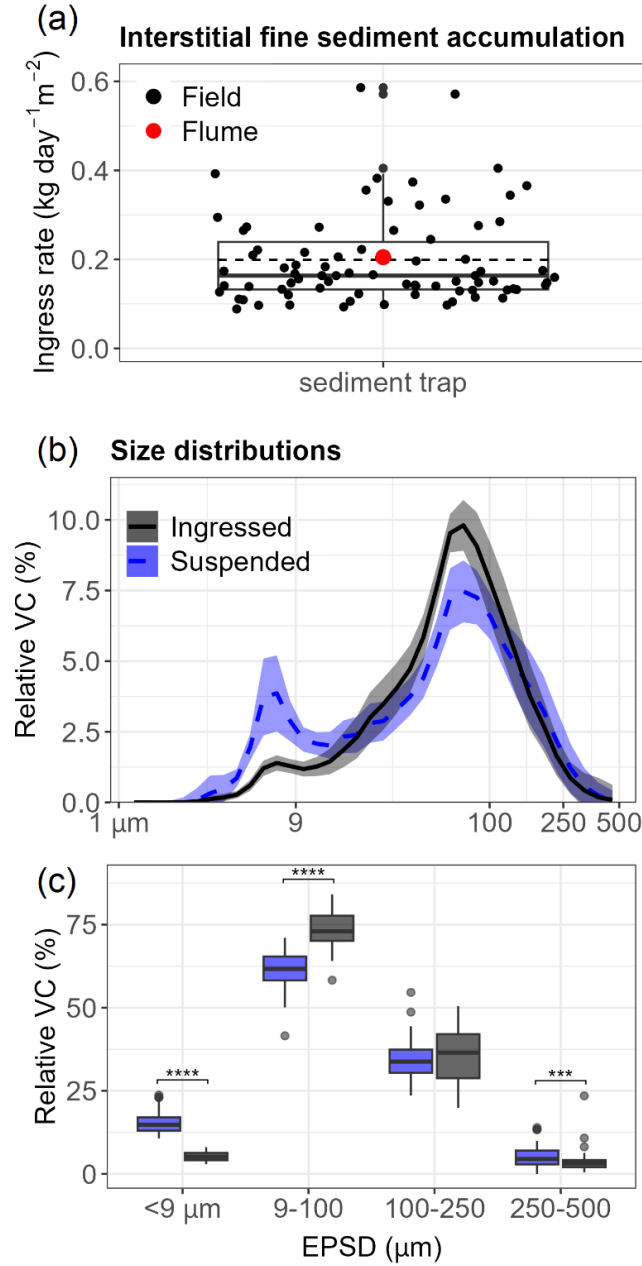


Figure 6.5. Ingress rates measured during flume and field assessments (a). EPSP measurements (b; source: Maltauro et al., 2024a), and Mann–Whitney U test pairwise comparison of size classes (c) regarding suspended ($n = 64$, regarding 16 in-situ assessments at the four study sites) and ingressed ($n = 84$, regarding particles measured in seven ingress trap deployment cycles in the four study sites, in triplicate). p-values: *** $p < 0.001$, and **** $p < 0.0001$. Median, upper, and lower quartiles; whiskers indicate the range spanning 1.5 times the interquartile range. Dashed line in (a) indicates the mean of *in-situ* measured values.

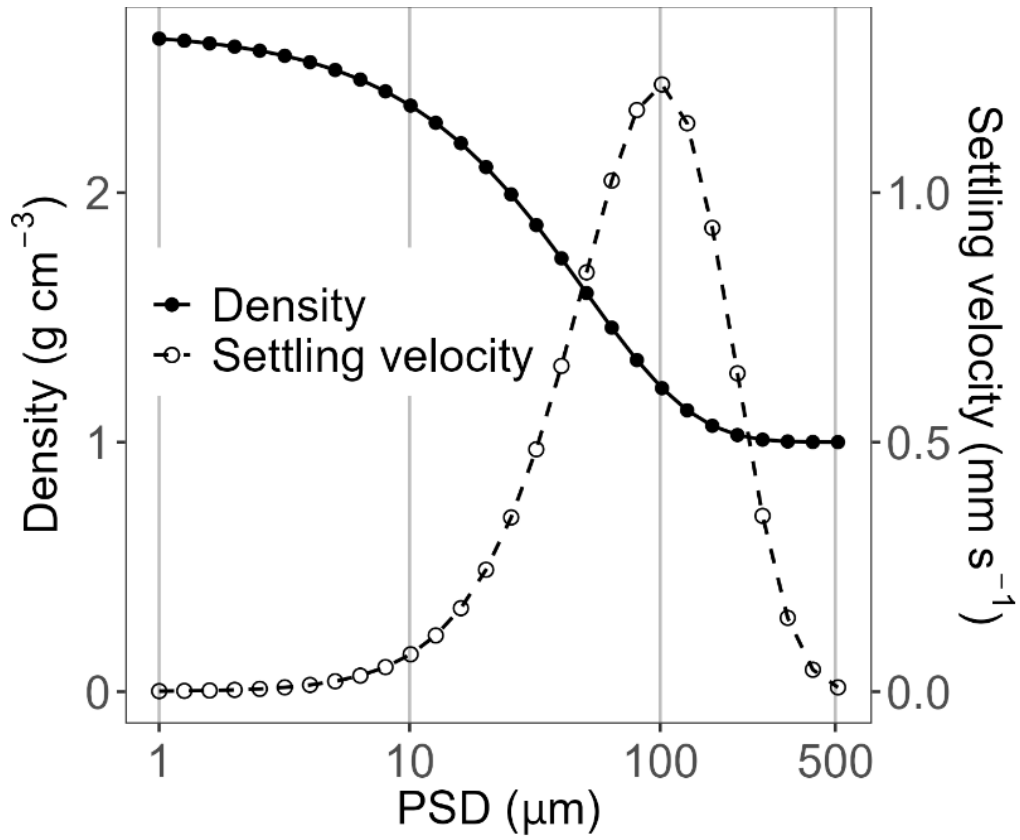


Figure 6.6. Settling velocity and density relationships according to floc size (absolute PSD <63 μm), determined through empirical and theoretical approaches during the calibration of the FLUME model. Data points represent the flocculated size classes used to determine densities and settling velocities empirically with the FLUME model, and lines represent the trends in the data to aid visualization.

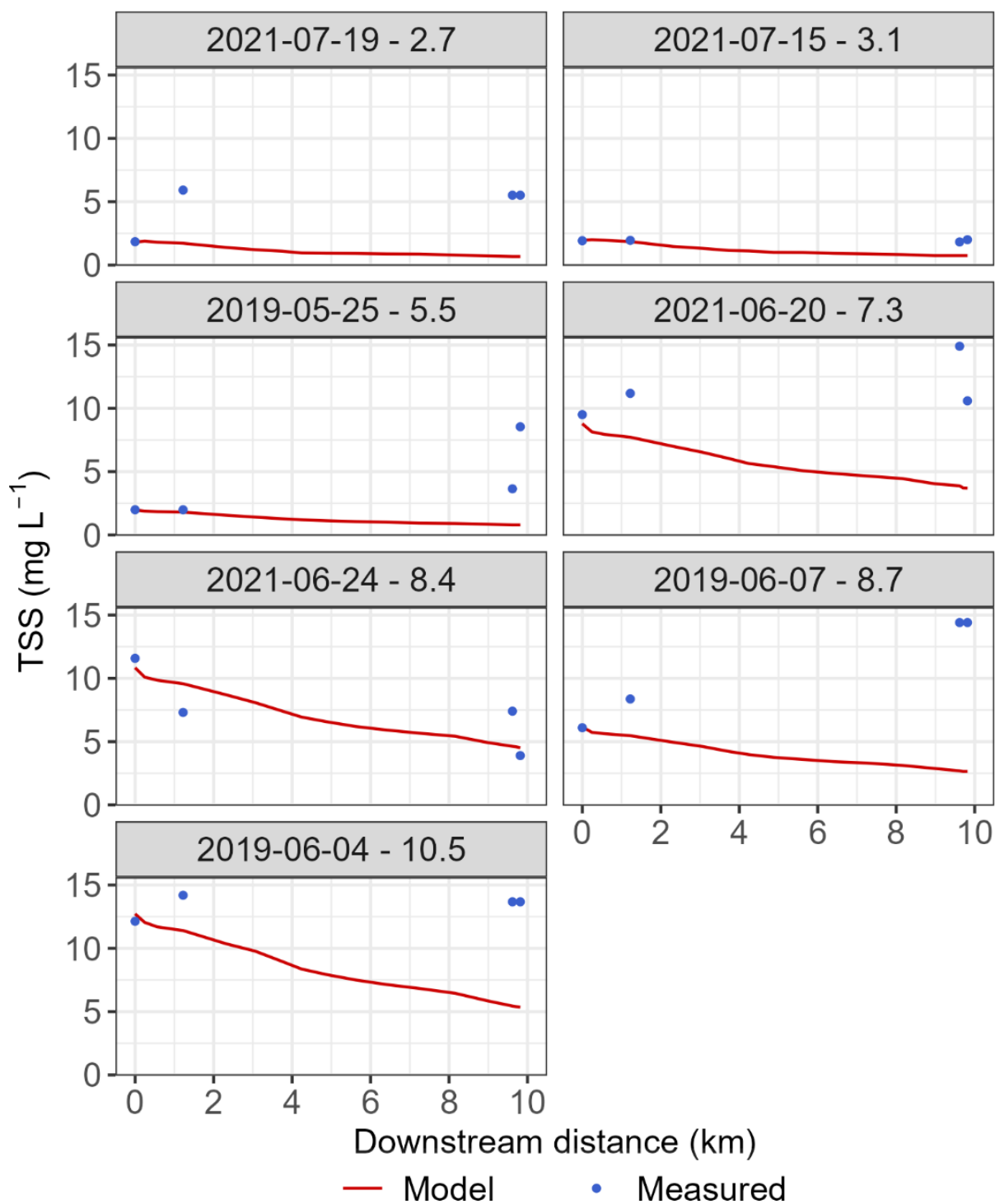


Figure 6.7. Concentration of suspended solids modelled with RIVFLOC and measured *in-situ* for the study reach of the Crowsnest River at different dates (year-month-day) and discharge events ($\text{m}^3 \text{s}^{-1}$).

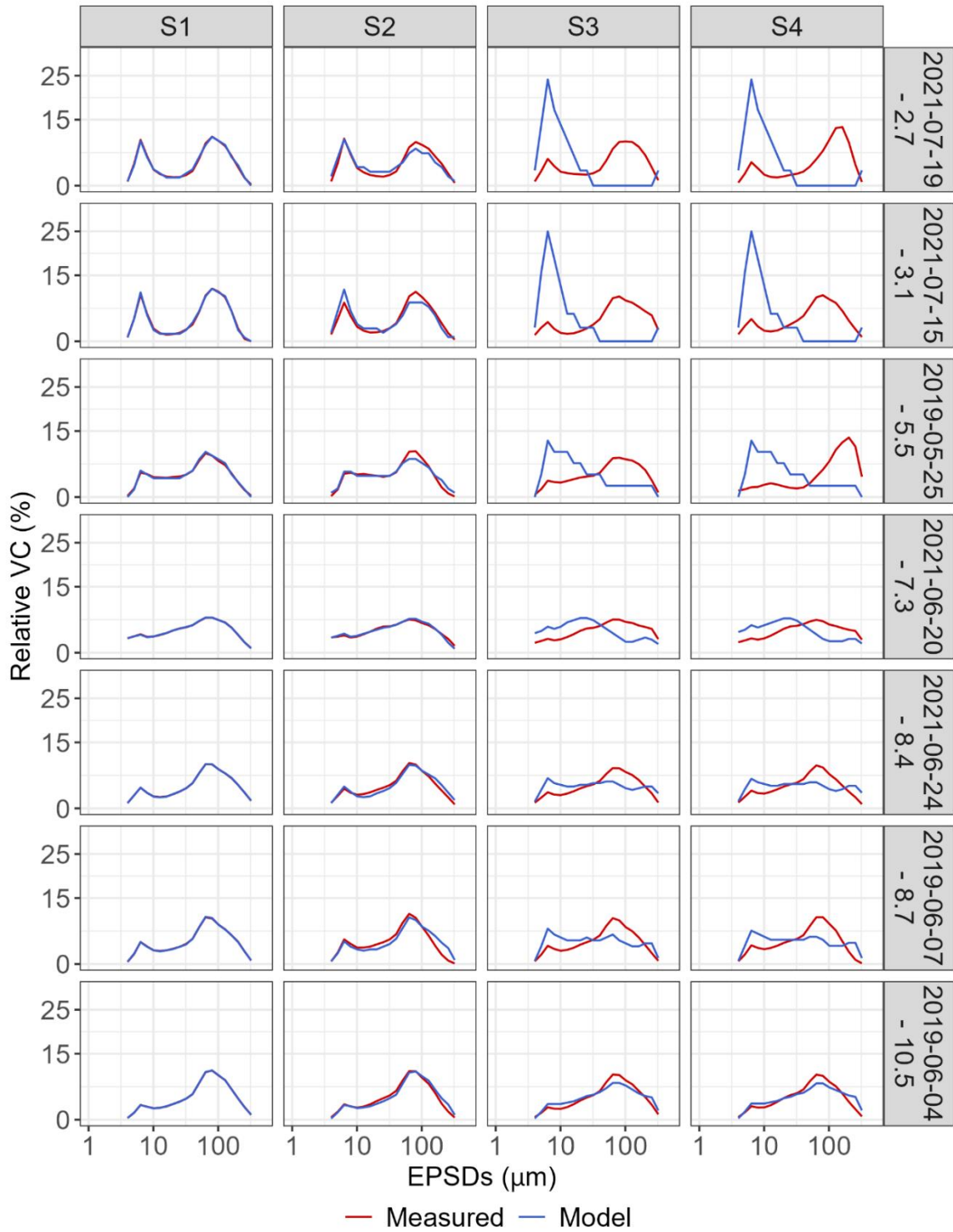


Figure 6.8. Relative volume concentration (VC) of effective particle size distributions (EPSDs) modelled with RIVFLOC and measured *in-situ* for different dates (year-month-day) and discharge events ($\text{m}^3 \text{s}^{-1}$).

6.5. Discussion

6.5.1. Cohesive sediment transport dynamics observed in the flume

The deposition experiments conducted in the rotating annular flume allowed the determination of the critical bed shear stress required for the gravitational deposition of suspended particles. The τ_{CrDP} value was comparable to other studies evaluated using similar experimental conditions (Table 6.2). However, it was an order of magnitude higher than hydrophobic sediments affected by bitumen contamination (higher buoyancy properties) (Droppo and Krishnappan, 2016), and lower than sediments from the Elbow River (where upstream land use is more urbanized relative to our sites) (Glasbergen et al., 2015). In the context of this study, shear stresses in the assessed river reaches are consistently higher than the critical threshold for deposition. Accordingly, suspended sediment deposition is not predicted to occur by the modelling framework, thereby not leading to the formation of surficial deposits of cohesive sediment within the study river reach. As cohesive sediment deposits were assumed not to form under the range of modelled shear stresses, erosion processes have not been incorporated into the modelling framework. However, field observations showed that bed surficial deposits can be discontinuously present within the 10 km reach of the Crowsnest River, and their erosion, as observed through the flume experiments, can have important implications on river health and cohesive sediment transport dynamics.

Table 6.2. Range of critical shear stresses for erosion and deposition measured in the rotating annular flume.

Study	River	Erosion		Deposition	
		Consolidation period (hours)	τ_{CRE} (Pa)	τ_{CRDP} (Pa)	τ_{CRDK} (Pa)
This study	Crowsnest River (AB, CA)	24	0.12	0.05	0.5
Krishnappan (2006) and Krishnappan (2022) (Stone et al., 2008)	Hay River (NWT, CA)	24	0.12	0.08	0.40
		48	0.16		
		168	0.21		
Krishnappan and Marsalek (2002a, 2002b)	Kingston - storm water pond (ON, CA)	41	0.10	0.04 ^a	0.40 ^a
		138	0.15		
Droppo & Krishnappan (2016) and Droppo et al. (2015)	Ells River (AB, CA) bitumen contaminated sediment	24	0.049	0.004	0.23 ^a
		72	0.145		
		168	0.194		
Garcia-Aragon et al. (2011)	Athabasca River	24	0.16		
		72	0.21		
		168	0.26		
Glasbergen et al. (2015)	Elbow River (AB, CA)	39	0.21	0.11	not reported
		133			
Krishnappan et al. (2020) and Stone et al. (2021a)	Taw River (Devon, UK)	22	0.09	0.06	0.33
		38			
		160			
Droppo et al. (2011)	South Nation River (ON, CA)	22.5	0.165	0.05	0.31 ^a
		45	0.123		
		92			
Stone et al. (2011) and Stone et al. (2021)	Lynx Creek (wildfire affected watershed) (AB, CA)	48	0.12	not reported	0.40
		168	0.23		0.64
		336	0.31		0.72
	Castle River (unburned watershed) (AB, CA)	48	0.105	not reported	0.20
		168	0.141		0.50
		336	0.165		0.45

^avalues estimated from reported study.

As described by others, the initial resuspension of sediment, classified as Type 1A erosion, represents the erosion of the loosely-bound surficial fine-grained layer (SFGL) (Droppo and Stone, 1994; Legout et al., 2018; Stone et al., 2011). The resuspension of the SFGL entrained ~3% of the sediment that was deposited in the flume (Figure 6.4B). The SFGL corresponded to the uppermost layer of deposited sediment, which consists of flocs with lower density, higher water content, and porosity relative to the layer beneath (Droppo and Amos, 2001). The entrainment observed at ≥ 0.16 Pa comprises the resuspension of more consolidated bed layers, which, due to the action of self-weight as they accumulate, undergo dewatering processes, becoming more dense and stable (Droppo and Amos, 2001).

Deposited sediments develop complex interactions with microorganisms at both the SFGL and deeper consolidated layers (Gerbersdorf and Wieprecht, 2015). However, the role of eroded cohesive sediment in the transport of sediment-associated pathogens is well-accepted (Droppo et al., 2015; Gerbersdorf and Wieprecht, 2015). Accordingly, previous observations on the EPSDs of eroded deposits from the Crowsnest River demonstrated that once entrained, bed flocs were able to maintain the coarser flocculated sizes developed in the consolidation process (Maltauro et al., 2024c), which can have implications for the sediment-associated transport and fate of pathogens and contaminants.

The shear stress required to initiate the erosion of cohesive beds through both Types 1A and B has been reported to depend on the nature of the sediment (i.e., sediment sources, including disturbed/undisturbed conditions at the source) and the consolidation period of deposited particles (Table 6.2). For instance, in the study conducted by Stone et al. (2011), which evaluated the effects of the Lost Creek Wildfire on the sediment of Lynx Creek, the authors observed higher τ_{CrE} in the sediment affected by the wildfire relative to an unburned reference, and increasing τ_{CrE} values with

increasing consolidation periods. While similar effects of consolidation on increasing erosion thresholds have been made elsewhere (Droppo and Krishnappan, 2016; Garcia-Aragon et al., 2011; Krishnappan, 2022; Stone et al., 2008), these effects are not always observed, and increasing consolidation periods have shown either no effects on τ_{CrE} (Glasbergen et al., 2015; Krishnappan et al., 2020), or even decreasing effects on the τ_{CrE} (Droppo et al., 2011) (Table 6.2). Further, investigations have also shown the high spatial variability in erosion thresholds in both lowland (Grabowski et al., 2012) and mountainous (Haddad et al., 2022) rivers. As such, in a river such as the Crowsnest, where the discontinuous sediment deposits (limited to zones of slack water and vegetated bars) might be “protected” from average discharges, high-flow energy events can reconnect these areas to the main channel, leading to sediment resuspension. As elucidated by Watts et al. (2021), while studying the Crowsnest River, upstream disturbances, such as the Lost Creek Wildfire, can present legacy downstream effects due to such dynamics, as resuspension events can also remobilize sediment-associated phosphorus.

Despite the high shear stresses observed along the four sites in the Crowsnest River, which prevents the development of surficial deposits and their further infiltration into the channel bed, interstitial fine sediment accumulation has been previously reported from a thorough field campaign (Maltauro et al., 2024a). Accordingly, nearly all available suspended sediment infiltrated the gravel framework during the ingress experiment. This was contrary to experiment D4, which was conducted under the same applied shear stress as I6, but which resulted in the deposition of ~25% of the available suspended sediment. The high interstitial entrapment of suspended particles observed in the flume experiment I6 is in accordance with similar studies (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018). This ingress process occurring under shear stresses that are much higher than the critical shear stress for deposition is attributed

to the effects of advective transport and/or turbulent diffusion (Droppo and Krishnappan, 2016; Packman et al., 2004; Tonina and Buffington, 2009, 2007), which occurs due to the interaction of the porous gravel-bed framework with the flow field.

According to our observations and findings from related studies (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018), no exfiltration (interstitial fine sediment flushing) was recorded after the occurrence of ingress. However, all bed shear stresses generated on our flume assessments and similar studies (Glasbergen et al., 2015; Krishnappan and Engel, 2006; Mooneyham and Strom, 2018) were relatively lower than bed shear stresses that can develop *in-situ*. These relatively lower shear stresses in rotating flumes occur because if fast rotations are applied to the flumes, secondary flows can be generated due to centrifugal forces, thereby compromising the uniform distribution of shear stress (Krishnappan, 1993).

The ingress rate of $0.20 \text{ kg m}^{-2} \text{ day}^{-1}$ recorded in the flume is comparable to the rates of 0.21 (Glasbergen, 2013) and $0.55 \text{ kg m}^{-2} \text{ day}^{-1}$ (Krishnappan and Engel, 2006) measured in studies using the same annular flume for sediments of the Elbow River and pure clay mixtures, respectively. The good agreement between flume and field observations (Figure 6.5A), reflects the high fine sediment interstitial accumulation capacity of this gravel-bed river. Further, the good agreement between field and flume ingress rates is likely attributable to the lack of colmation processes in either flume or field observations. We believe that these results would have differed if any interstitial clogging or saturation (highly common in lowland gravel-bed rivers (Brunke, 1999; Harper et al., 2017; Mathers et al., 2019)) had occurred since clogged bed pores would inhibit further infiltration of fine sediment.

6.5.2. RIVFLOC model application and implication of the observed results

As previously discussed, through all assessed discharges, ranging from 2.7 to 10.5 m³ s⁻¹, bed shear stress values calculated with the MOBED model were higher than the critical shear stress for deposition of the studied cohesive sediment (Table 6.1). As such, no deposition by settling was calculated by RIVFLOC, and downstream reductions in modelled TSS concentrations were solely predicted based on cohesive sediment ingress, which, as discussed, can occur under shear stresses higher than the critical shear for deposition due to advective transport and/or turbulent diffusion (Packman et al., 2004; Reidenbach et al., 2010; Tonina and Buffington, 2009, 2007). Given the different suspended sediment supply regimes between flume (known initial concentration) and field (point and non-point sources of cohesive sediment along the 10 km study reach) settings and given that defining *in-situ* cohesive sediment sources was out of the scope of this study, model validation with field observations was not conducted. Rather, this semi-empirical model has been carefully calibrated and validated with flume data (controlled environment), and differences between the model predictions and field observations have been used as a foundation for our discussions. Nevertheless, our comparable measurements of ingress rates between flume and field datasets (Figure 6.5A), lead us to believe that the high interstitial accumulation predicted by the model might be correct. Although ingress rates in this study have been only used to validate ingress rates measured in the flume, previous studies built on the rich and unique dataset regarding the aforementioned ingress measurements have discussed the measurement variability associated with samplers deployed (Maltauro et al., 2024b), and the hydro-sedimentological drivers governing the ingress of these particles (Maltauro et al., 2024a).

Despite the general good agreement between field and flume measurements of ingress, *in-situ* downstream changes in suspended sediment concentrations were not as high as the modelled

predictions (Figure 6.7). The discrepancy between observed and model predictions likely stems from the different sources of cohesive sediment from tributary inflow, bank, and in-channel sources between the upstream and downstream cross-sections that were not accounted for in the modelling framework. While the exact extent of channel and non-channel cohesive sediment contributions is uncertain and has not been investigated in the context of this study for model validation purposes, field observations on sediment connectivity in this river system, as discussed below, allow us to infer potential mechanisms leading to observed differences between *in-situ* and modelled datasets.

Cumulative watershed effects from both natural and anthropogenic landscape disturbances have been observed to increase downstream pressures in sediment mobilization in the Crowsnest River (Stone et al., 2014; Watt et al., 2021). For instance, upstream of site 4, land use and landscape disturbances of both natural (wildfire) and anthropogenic nature account for ~25% of catchment coverage (Watt et al., 2021). Despite the known effects of landscape disturbances on sediment sources within the drainage area of the Crowsnest River, sediment delivery in the region is highly dependent on precipitation-driven hillslope erosion and, consequently, high discharge events (Maltauro et al., 2023; Silins et al., 2009; Stone et al., 2014). Our results, however, demonstrated that differences between modelled and measured suspended sediment concentrations were consistently observed for high and low discharges. These consistent discrepancies suggest that, while non-channel sources are more likely to explain differences in suspended sediment concentration during higher flows, channel sources would likely play an important role during the lower range of observed flows. Within the observed flow conditions in the Crowsnest River, potential channel sources of cohesive sediment would likely include bed erosion of surficial deposits in the main channel and bank erosion from headwater tributaries. However, the

availability and mobility of sediment sources depend on the nature of landscape disturbances, as well as precipitation and high discharge events to provide sufficient energy for their mobilization. Further, field observations suggest that the armoured and/or vegetated channels and streambanks were stable and likely did not contribute substantially to sediment inputs during the assessed flow conditions.

The extent to which exfiltration releases cohesive sediment from the gravel-bed framework without framework mobilization is largely understudied. Previous studies have demonstrated that bulk exfiltration of interstitial fine sediment is mostly limited to occur when the armour layer is mobilized; otherwise, flushing is restricted to the upper layers of the bed framework (Detert and Parker, 2010; Kuhnle et al., 2016; Schälchli, 1992). Notably, the occurrence of unimpeded static percolation (downwards interstitial infiltration by particle settling, if no surficial clogging occurs) (Gibson et al., 2009), can further shelter entrapped particles from exfiltration (Parker and Sutherland, 1990; Wharton et al., 2017). However, groundwater upwelling can assist interstitial flushing (Brunke, 1999), but limited investigations have assessed its role in exfiltration mechanisms (Dubuis and De Cesare, 2023) or on the impacts of interstitial loads in general (Casas-Mulet et al., 2018). Further studies are required to identify to what extent groundwater upwelling influences vertical and horizontal mechanisms of fine sediment infiltration or exfiltration. These exfiltration processes might be particularly important in the Crowsnest River where the alluvial aquifers in the river valley have a demonstrated role in groundwater discharge and flow regulation (Waterline, 2013).

Further, despite the high estimates of cohesive sediment interstitial accumulation at our sites, no interstitial clogging or bed saturation was observed across the gravel-bed. In turn, our observations regarding this oligotrophic, high-quality water river with a relatively undisturbed

drainage basin might suggest that infiltration/exfiltration processes of cohesive sediment might be more dynamic than previously thought. In the context of our previous observations on the importance of horizontal interstitial cohesive sediment accumulation (Maltauro et al., 2024a), we raise the following unanswered questions: What is the longitudinal distance that flocculated particles travel in the interstitial load comprising one element of the sediment budget? Given the relatively high ingress rates measured in the field and the flume, if sediment is exfiltrated from the bed interstices, how long does it travel in suspension before re-ingressing the gravel-bed? How does the interstitial consolidation, observed here through the coarser ingressed flocs, affect interstitial transport regimes? Here, a logical extension to the scope of future work could consider the role of benthic invertebrates and lithophilic fish, which have been observed to contribute to fine sediment channel bed storage dynamics (Rice et al., 2016; Wilkes et al., 2019).

Flocculation has been observed to play an important role on the transport of cohesive sediments in different river systems (Droppo et al., 1998; Droppo and Krishnappan, 2016; Livsey et al., 2022). Previous observations on this oligotrophic gravel-bed river have demonstrated the importance of shear-dependent flocculation on the suspended transport of cohesive particles (Maltauro et al., 2023). Accordingly, flocculation was an important component of our selected modelling framework, which can be observed through modelled EPSDs (Figure 6.8). While good model predictions of EPSDs were obtained for the highest modelled discharge condition, lower discharges resulted in particle fining at the downstream sites (Figure 6.8). In the model, such relationships are a consequence of cohesive sediment ingress, which is calculated as a function of settling velocity according to particle size (Krishnappan and Engel, 2006). Here, the empirical determination of density and settling velocities (Figure 6.6) showed that flocculation increased the settling velocity of flocs $\sim 100\ \mu\text{m}$, leading to their preferential bed accumulation –during ingress

and deposition flume experiments. This empirical assessment is in accordance with previous field investigations in which we observed the higher volume of $\sim 100\ \mu\text{m}$ particles within ingressed relative to suspended samples (Figure 6.5C; Maltauro et al., 2024a). However, differences in EPSDs between upstream and downstream sites were not as expressive on *in-situ* measurements relative to the modelled predictions (Figure 6.8). We believe that such differences between modelled and measured results can also be attributed to the different cohesive sediment sources between sites 1 and 4, as discussed above, that are not incorporated into the modelling framework. These differences highlight the need for future investigation as interstitial cohesive sediment exfiltration might affect flocculation processes acting on the suspended sediment load.

Given the biological, chemical, and physical impacts of excess cohesive sediments and potential associated pollutants, understanding their transport and fate is imperative for effective watershed management. We observed that considerable amounts of cohesive sediment are stored in the gravel interstices. If, as observed in the literature, most exfiltration occurs when the bed armour is entrained, a rough estimation using the critical shear stress (Shields et al., 1936) for entrainment of bed particles represented by the 70th percentile (70 mm) suggests that the flow energy required to mobilize the armour layer and promote bulk interstitial flushing has a ~ 40 year return period using the annual series of maximum discharges since 1950 (Environment Canada, 2021). Although many uncertainties are inherently associated with such estimations, these calculations point to the potential of the gravel bed to play an important role in the legacy effects of previous landscape (natural and anthropogenic) disturbances.

6.5.3. Study limitations

Modelling cohesive sediment transport is notably challenging, given the complexities of flocculation processes. Complexities are further exacerbated when modelling floc transport in gravel-bed rivers, given the sediment interaction with the turbulent flow field and the porous gravel-bed framework. Here, our selected model was validated with the flume experiments, and, as discussed, the ingress rates measured in the flume were in alignment with field observations, which supported the calibration of the ingress coefficient of RIVFLOC. However, model assumptions, such as the utilized cohesion coefficient, likely oversimplify complex processes of flocculation. For instance, and as previously reported in Maltauro et al. (2023), different floc attachment strengths, according to floc size, would be more accurately represented by the model through the use of a variable cohesion coefficient according to floc size. Here, the consideration of a single cohesion factor likely underestimates the predicted volume of flocs sizes around the $\sim 100 \mu\text{m}$ (second modal peak of Figure 6.8), which are more strongly bounded and more likely to be predominant in the suspension, as previously observed by Maltauro et al. (2023). Nonetheless, while we acknowledge that more suspended particles $\sim 100 \mu\text{m}$ could have been predicted with a variable cohesion coefficient, we still believe that the preferential ingress would have been predicted given our corroborating previous field observations (Maltauro et al., 2024a), and the settling velocities observed in this study for this floc size class. Further, it is important to state that the consideration of a single value for the ingress coefficient within the 10 km reach is also a simplification, considering the one-dimensional application of the RIVFLOC model. Accordingly, at the field scale, variations in ingress rates are expected to occur according to geomorphology and flow field. Ingress rates, as previously discussed, are also affected by the fine sediment saturation of the channel bed framework. Although saturation was not identified at any of our sites, it has

been consistently reported in lower-energy gravel-bed river systems, and should be considered accordingly. We also highlight that the entrapment component in the RIVFLOC model currently does not account for the progressive reduction in ingress rates that would be expected with the infilling of interstitial pore spaces. While it is likely that this has not affected our results due to the lack of interstitial fine sediment saturation at our study sites, and the importance of horizontal ingress mechanisms likely due to interstitial load, as previously reported (Maltauro et al., 2024a), we note that RIVFLOC might potentially overestimate ingress processes in gravel-bed rivers experiencing fine sediment interstitial saturation. Finally, many knowledge gaps still impart uncertainties in the model predictions and prevent model validation at the field scale. Further opportunities for additional research include: the assessment of the impacts of groundwater upwelling on interstitial cohesive sediment exfiltration; the impacts of the interstitial load on cohesive sediment propagation downstream; the evaluation of the age/residence time of interstitial cohesive sediment, and; the potential role of benthic invertebrates and lithophilic fish on cohesive sediment storage dynamics.

6.6. Conclusion

This study is the first to apply the utilized modelling framework beyond flume experiments, expanding its application to field measurements of EPSDs, suspended sediment concentrations, and ingress rates. Due to the high flow energy in the main channel, the model predicted no settling by gravity. Within the range of observed discharges, fine interstitial sediment accumulation was invariably driven by ingress occurring under turbulent flows. Model estimates indicate that as much as 60% of suspended sediment is expected to ingress along the ~10 km study reach. We observed that cohesive particles were predominantly transported in flocculated form, and due to

flocculation, the increased settling velocities resulted in elevated ingress of particles sized 9 – 100 μm . Further, despite excluding erosion fluxes of sediment deposits (only discontinuously present in the study reach) from the modelling framework, we observed, from flume assessments, the effects of biostabilization and consolidation on the resuspension of cohesive deposits. These findings bring novel perspectives into the propagation and storage dynamics of cohesive sediments in gravel-bed rivers and clearly elucidate the need for further strategic investigation to improve our mechanistic understanding of cohesive sediment transport.

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Chapter 7. Conclusions and recommendations for future research

7.1. Synthesis and implications

Advancing knowledge on fine sediment transport and fate is critically important, given the potential of these particles to degrade water quality, impair hyporheic exchanges, reduce aquatic system health, and challenge drinking water treatment. Due to the lack of observations *in-situ* and the complexity of processes affecting flocculation and fine sediment ingress in gravel-bed rivers, most sediment transport models disregard these processes, which can subsequently lead to inaccurate estimates of fine sediment propagation and storage. In this thesis, *in-situ* and flume studies were conducted to evaluate the flocculation properties of suspended and ingressed cohesive solids, quantify their interstitial accumulation rates, and model their propagation and fate in a gravel-bed river. To the best of my knowledge, the dataset gathered in this study is the first of its kind, given its richness in spatial and temporal scales and its integration of field and flume observations. Notably, this unique dataset establishes novel connections between suspended and interstitial fine solids, and it expands existing knowledge from previous studies regarding the mechanistic understanding of flocculation and ingress properties of cohesive solids in gravel-bed rivers. The key findings and novelty aspects of this thesis are outlined below.

In Chapter 2, a spatially and temporally rich dataset allowed the characterization of the flocculation properties of suspended solids in the Crowsnest River. The time series of *in-situ* effective particle size distributions demonstrated that, while bed shear stress was positively correlated with floc sizes within the microfloc size range ($\sim 100\ \mu\text{m}$), it was negatively correlated with the largest flocs, which were mostly observed to form in lower energy flows. These observations demonstrated that, despite the characteristic turbulent flow field and in accordance with the general theory of flocculation, particles were predominantly transported as flocs, with

effective sizes varying as a function of the flow energy. These results support previous observations made in coastal and estuarine regions about the different strengths of floc attachment according to floc sizes. Accordingly, different attachment strengths have implications for the modelling framework described in Chapter 6, which considers a constant, empirically obtained value for the cohesion factor. The observations from Chapter 2 and Chapter 4 (discussed below) suggest that considering a variable cohesion factor according to floc size could incorporate the prevalence of certain (more strongly attached) size classes into the modelling framework, which could improve the predictions of multimodal particle size distributions.

In Chapters 3 and 4, a unique field campaign was conducted, in which >250 samplers comprising triplicates of three sediment trap designs were deployed across four study sites in the Crowsnest River, over a range of flow conditions (stormflow and base flow). In Chapter 3, sediment trap designs were evaluated and compared. The dataset generated demonstrated the high variability in ingress measurements within particle sizes 0.5 to 2 mm (predominantly non-cohesive fine sediment), while lower variability was observed for particles <0.5 mm (effective size, predominantly consisting of flocculated solids). To my knowledge, no other studies have deployed triplicates of samplers with the objective of assessing ingress variability. These findings lend valuable significance to future studies, as they reveal and quantify the high natural variability that can occur in ingress processes. The results obtained in Chapter 3 also allowed the evaluation of methodological practices used for estimating vertical and horizontal ingress mechanisms. To my knowledge, this is the first study to evaluate such methodological practices by incorporating the three commonly used designs of ingress samplers. These observations advance our understanding of methodological approaches and can be used to improve the accuracy of field assessments of

ingress mechanisms, which, in turn, are required to improve knowledge and refine models for fine sediment storage.

In Chapter 4, results from sediment traps were used to evaluate the flocculation and ingress properties of interstitial cohesive solids in the Crowsnest River. Hydraulic (discharge, water depth, Froude number, bed shear stress, and stream power) and sedimentological (suspended solids concentration by mass and volume) parameters obtained through *in-situ* and modelled measurements were linearly regressed with ingress rates of fine sediment. Non-cohesive particles (0.5 to 2 mm) correlated poorly with hydro-sedimentological parameters, while better correlations were observed for particles <0.5 mm (effective size, predominantly consisting of flocculated solids). Ingress rates of flocculated particles were higher under higher flow energy, and ingress was predominantly horizontal during lower energy flows. Comparisons between effective and absolute particle size distributions showed modal peak similarities between the ingressed and suspended solids, which suggests that particles are likely from the same catchment source (channel or non-channel) or that their transport is influenced by dynamic exchanges between ingress and exfiltration. However, ingressed particles were significantly coarser than suspended particles, demonstrating that ingress is either size-selective for particles $\sim 67\ \mu\text{m}$ and/or flocculation is favored within the interstitial load. These observations raise several questions regarding interstitial infiltration and interstitial load, as discussed in section 7.2. To the best of my knowledge, the data in Chapter 4 is the first of its kind to evaluate floc properties and hydro-sedimentological drivers of cohesive solids ingress in a gravel-bed river. Notably, these findings advance current knowledge on ingress processes according to different flow conditions and the effects of flocculation on cohesive sediment storage in a gravel-bed river. Further, findings from Chapter 4 were also

critically important in assisting with the calibration of the modelling framework applied, which is discussed in Chapter 6.

In Chapters 5 and 6, a globally unique rotating annular flume was used to evaluate the flocculation processes and transport properties of cohesive sediments collected from the Crowsnest River. In Chapter 5, effective particle size distributions of cohesive sediment were evaluated in deposition, ingress, and erosion experiments using different bed configurations over a range of flow conditions. The findings from the deposition experiments reaffirmed the importance of shear-dependent flocculation, which is in accordance with observations made in Chapter 2. Differently than the steady state reached by EPSDs in the deposition experiment, and, to my best knowledge, the first observation of its kind, the modes of effective particle size distributions in the ingress experiment varied with the progression of the test, demonstrating the complex flocculation process due to the flow interaction with the gravel bed and elucidating the need for future investigations of such interactions. In the erosion experiment, bed consolidation led to the resuspension of larger flocs, which – contrary to observations made in other studies – were able to maintain the larger floc sizes within the flow field after entrainment, suggesting higher floc stability due to bed consolidation on resuspended flocs. The findings from Chapter 5 suggest a potential sequence of transport processes of cohesive sediment in a gravel-bed river: initially deposited solids flocculate into coarser flocs through bed consolidation; coarser bed flocs can maintain their size after entrainment; subsequently, coarser flocs can preferentially deposit on or ingress into the channel bed; finally, while deposited particles can resuspend under appropriate flow conditions, no interstitial exfiltration was observed in the ingress experiment.

In Chapter 6, the flume experiments were used to calibrate and validate a semi-empirical fine sediment transport model (RIVFLOC), which was then applied to the observed field

conditions. To the best of my knowledge, RIVFLOC is the only model that incorporates flocculation and ingress processes under high-shear stress conditions into its parameterization. For this study reach, the RIVFLOC model estimated that ~60% of the suspended flocs in the water column will ingress in the gravel-bed bed between upstream and downstream sites, regardless of the higher or lower assessed flow conditions. This estimation cannot be fully validated under *in-situ* conditions given the continuous sources of fine sediment along the study reach, which prevents the assessment of an instantaneous sediment pulse such as in the flume. Nevertheless, the ingress rate measured in the flume, used for model calibration, was similar to the range of ingress rates measured in the field, as described in Chapter 4, thus supporting the observed model predictions. Further, in accordance with the field observations discussed in Chapter 4 and the flume experiments discussed in Chapter 5, the model predicted that ingress was also size-selective for most of the assessed flow conditions. Despite the raised unknowns regarding interstitial fine sediment exfiltration (discussed in section 7.2), the findings from the model application, along with the findings from Chapter 4, demonstrate the storage potential of the Crowsnest River, which has important implications for legacy effects of previous landscape disturbances. Although this modelling framework has been applied to several other studies, this is the first time the calibrated model (with flume experiments) has been applied to and compared with *in-situ* measurements of suspended sediment concentrations, effective particle size distributions, and ingress rates. Accordingly, the results of this study – through the integrated observations (in-situ, flume, and model) of ingress and flocculation processes – provide novel perspectives on cohesive sediment transport processes, such as quantitatively estimating the storage of fine sediment and identifying the potential of exfiltration mechanisms on the storage and propagation of these particles in this gravel-bed river.

7.2. Future research

While this novel study has presented some important insights and advances regarding flocculation and ingress processes in gravel-bed rivers, it also highlights the important knowledge gaps for further investigations. The observations of different floc attachment strengths as a function of floc size, observed in Chapters 2 and 5, suggest that adopting a variable cohesion coefficient in the flocculation component of the RIVFLOC model could improve the model predictions. Accordingly, the development of a variable coefficient is recommended. Further, future suspended sediment flocculation assessments could be conducted in smaller river reaches by evaluating lateral cross-sectional variations in EPSDs. Such lateral flocculation properties could be further modelled with RIVFLOC through its 2D approach. These observations have not been conducted elsewhere and still represent an important research gap in these gravel-bed rivers. Further, given the complexity of mechanisms operating on cohesive sediment fate and propagation in these gravel-bed rivers, artificial intelligence (AI) models could offer means for large-scale predictions (Livsey et al., 2022). However, AI models rely on large datasets for model calibration and validation, so performing data-rich studies is fundamental to enable AI applications, and this need currently precludes the widespread adoption of AI models.

Given its design, the rotating annular flume utilized in this study is a globally unique piece of scientific equipment. However, only two other studies (Glasbergen et al., 2015; Krishnappan, 2006) have utilized the flume with gravel substrates to evaluate ingress properties, and only the dataset presented in Chapter 5 has reported the size properties of flocculated particles during an ingress experiment. All these experiments were conducted with instantaneous fine sediment inputs. Accordingly, future studies could benefit from gravel-bed flume experiments in the rotating flume

under steady-state fine sediment inputs to assess: 1) ingress and flocculation processes, 2) colmation occurrence, and 3) fine sediment interstitial loads.

The results from Chapters 4 and 6 demonstrated the importance of the gravel bed in the storage of cohesive sediments in the study river. However, none of the gravel-bed sites in this study were saturated or clogged with interstitial sediment, and the occurrence of saturation could have led to very different results. Accordingly, future investigations on other geomorphic river features (e.g., thalweg, pool-and-riffle sequences, and tributary confluences) could expand our understanding of such storage processes by further investigating the hydro-sedimentological dynamics affecting flocculation and ingress processes on other river features. Further, in Chapter 4 of this study, turbulence effects were only assessed using mean flow parameters obtained from the flow model MOBED. As such, future research could benefit from investigating local site-specific turbulence effects (i.e., in-situ acoustic Doppler measurements) on the flocculation and ingress of cohesive sediment. Differences between model predictions and measured suspended sediment concentration (discussed in Chapter 6) suggest the potential contribution from interstitial fine sediments to the suspended load through exfiltration processes. Further, despite the important mechanisms of horizontal interstitial accumulation observed in Chapter 4, fine sediment exfiltration processes remain highly under-investigated. Future research is required to better understand: 1) the exfiltration mechanism of interstitial cohesive particles, which could be caused by groundwater upwelling or near-bed turbulence, 2) the longitudinal distances traveled in suspension before exfiltrated particles re-ingress, and 3) the timing of retention and longitudinal distances that cohesive particles travel within the interstitial load (Figure 7.1). Understanding these processes is fundamental to predicting impacts from landscape disturbances in gravel-bed river catchments.

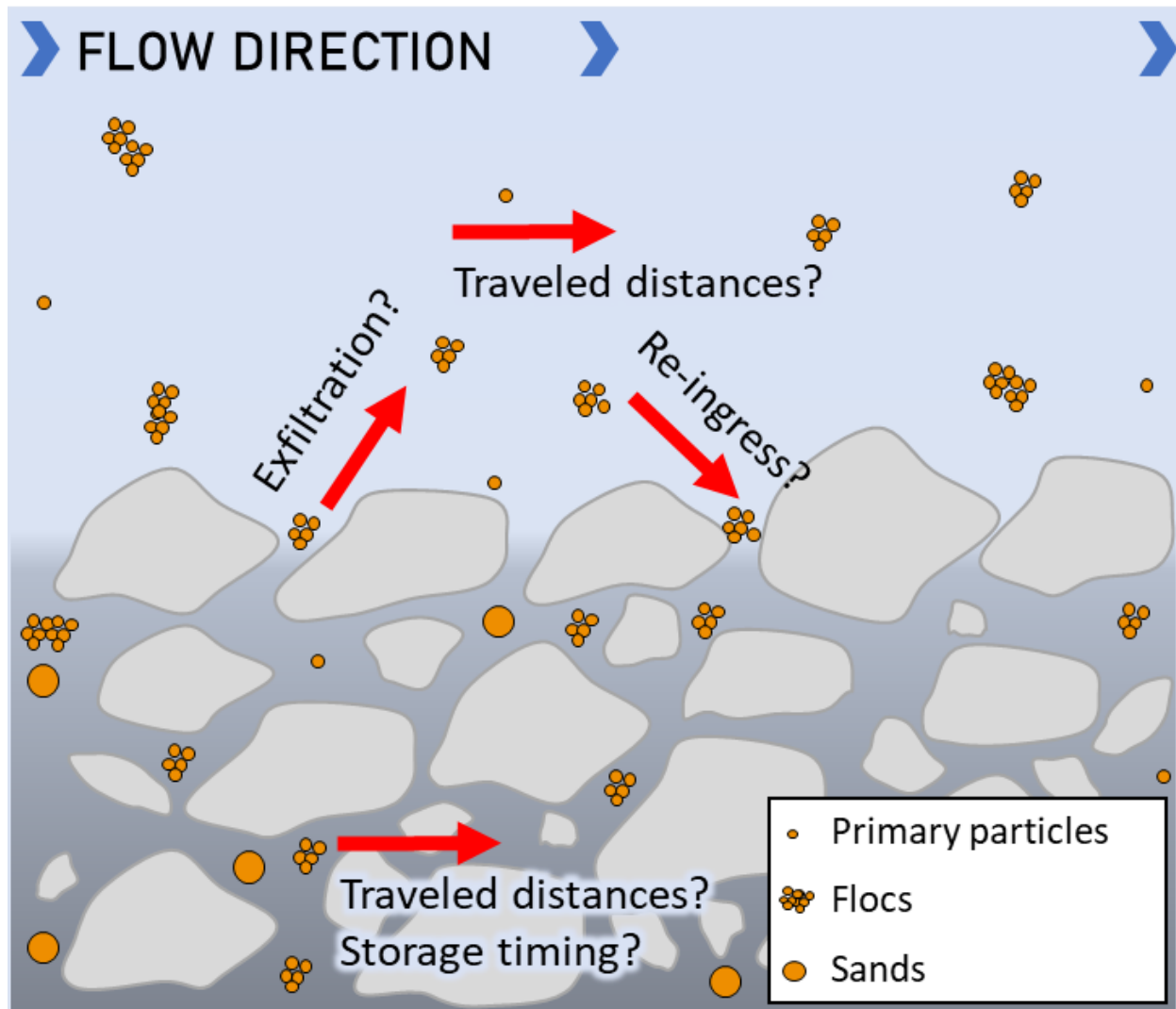


Figure 7.1. Conceptual diagram with components of the fine sediment transport and fate that require future investigation based on the differences between modelled and measured observations.

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Appendices

Appendix A

Appendix A provides supplementary material regarding Chapter 2.



Figure A.1. LISST-200x.



Figure A.2. Site 1



Figure A.3. Site 2



Figure A.4. Site 3



Figure A.4. Site 4



Figure A.5. Picture taken at the confluence of the Lyons Creek and the Crowsnest River on July 9th, 2019, demonstrating the contrasting turbidity between streams.

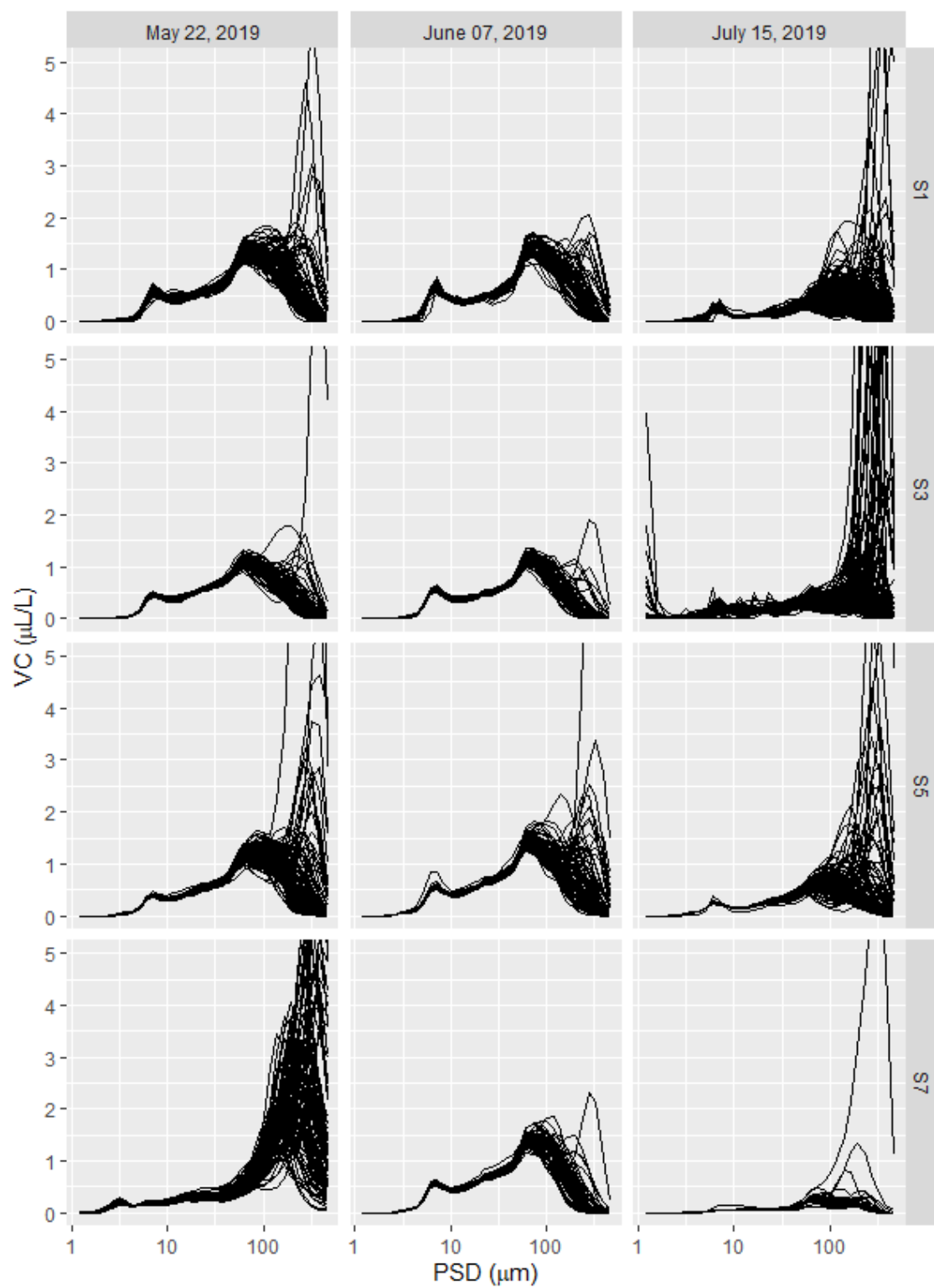


Figure A.6. Examples of the high natural variability in effective particle size distribution measurements.

Appendix B

Appendix B provides supplementary material regarding Chapter 3.

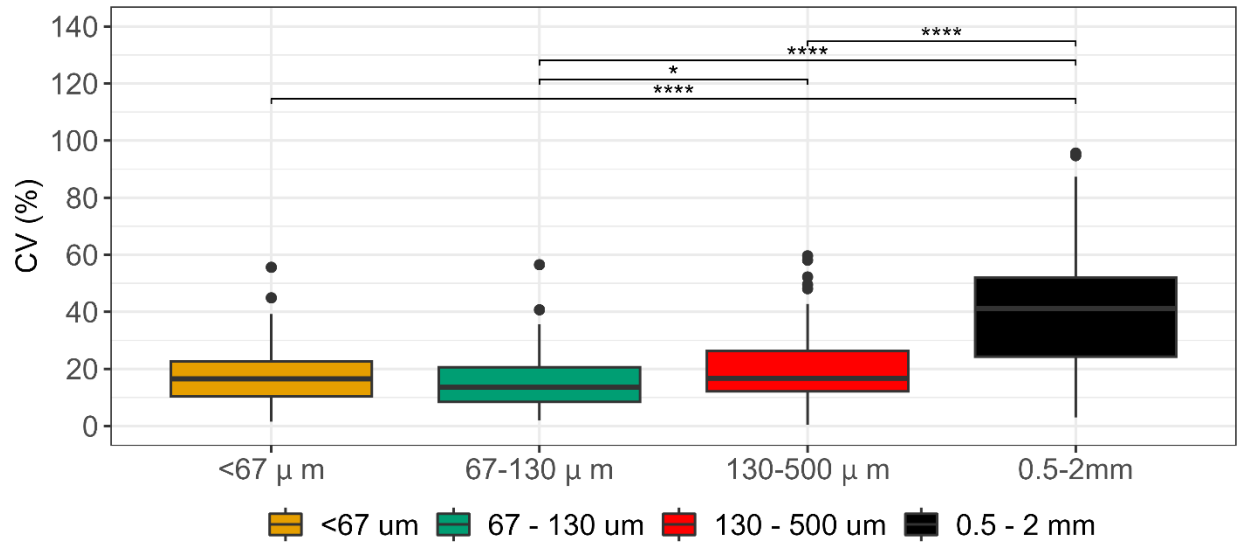


Figure B.1: Wilcoxon rank sum test pairwise comparison of coefficients of variation between size classes. $n = 84$ for each size class. Adjusted (Benjamini-Hochberg) p-values: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and **** $p < 0.0001$. Median, upper, and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range.



Figure B.2. Example of a sediment trap, design V.



Figure B.3. Example of a sediment trap, designs HV and H (deployed with a lid).



Figure B.4. One set of sediment traps deployed in site 2.



Figure B.5: Last deployment cycle (lowest discharges) at site 1

Appendix C

Appendix C provides supplementary material regarding Chapter 4.

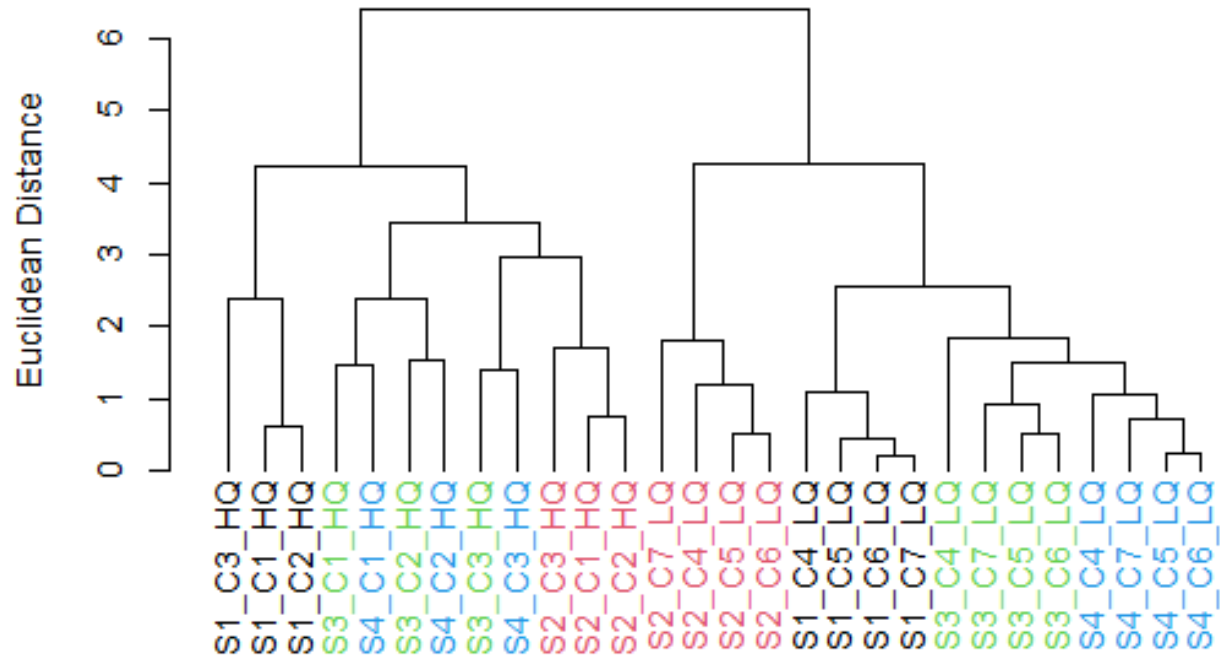


Figure C.1: Dendrogram using hydro-sedimentological variables (VC, TSS, Q, water depth, Froude number, bed shear stress, and unit stream power) for the four study sites, where C corresponds to deployment cycles.

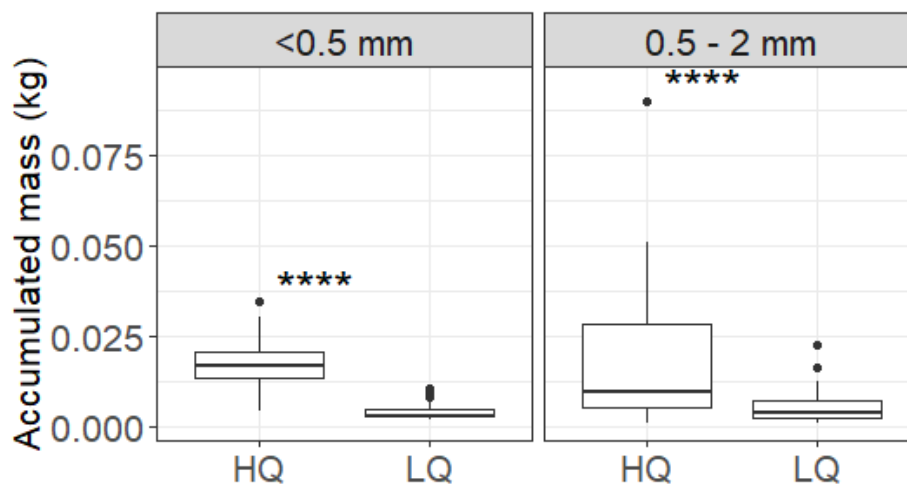


Figure C.2: Mann-Whitney U test pairwise comparison of accumulated mass of fine sediment from sediment trap HV between higher (HQ, $n = 36$) and lower (LQ, $n = 48$). Adjusted (Benjamini-Hochberg), **** $p < 0.0001$. Median, upper, and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range.

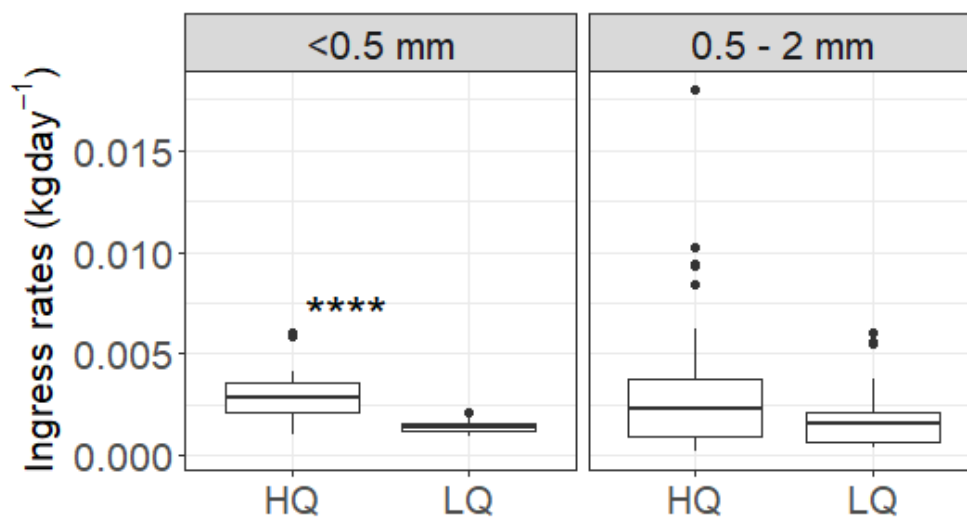


Figure C.3: Mann-Whitney U test pairwise comparison of ingress rates from sediment trap HV between higher (HQ, $n = 36$) and lower (LQ, $n = 48$). Adjusted (Benjamini-Hochberg), **** $p < 0.0001$. Median, upper, and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range.

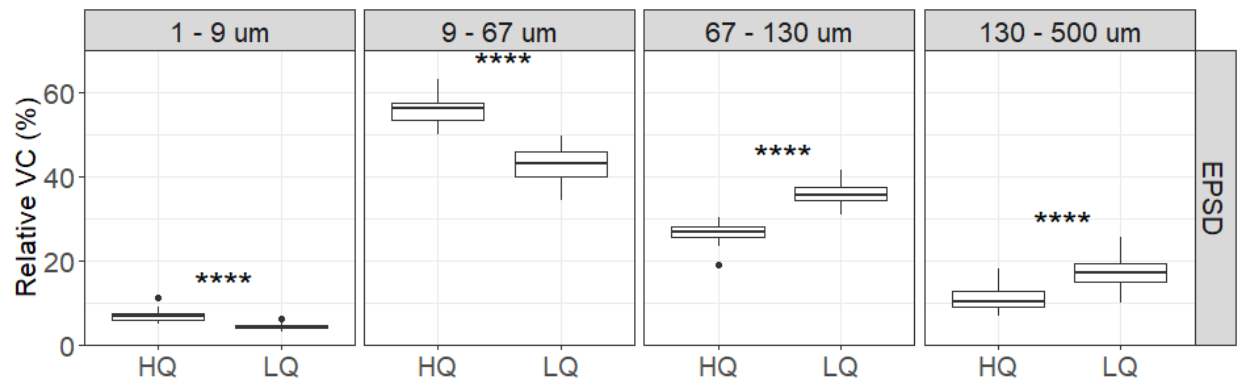


Figure C.4: Mann-Whitney U test pairwise comparison of relative volume concentration (VC) of ingressed particles from sediment trap HV between higher (HQ, n = 36) and lower (LQ, n = 48). Adjusted (Benjamini-Hochberg), ****p<0.0001. Median, upper, and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range.

Appendix D

Appendix D provides supplementary material regarding Chapter 5.



Figure D.1: Rotating annular flume

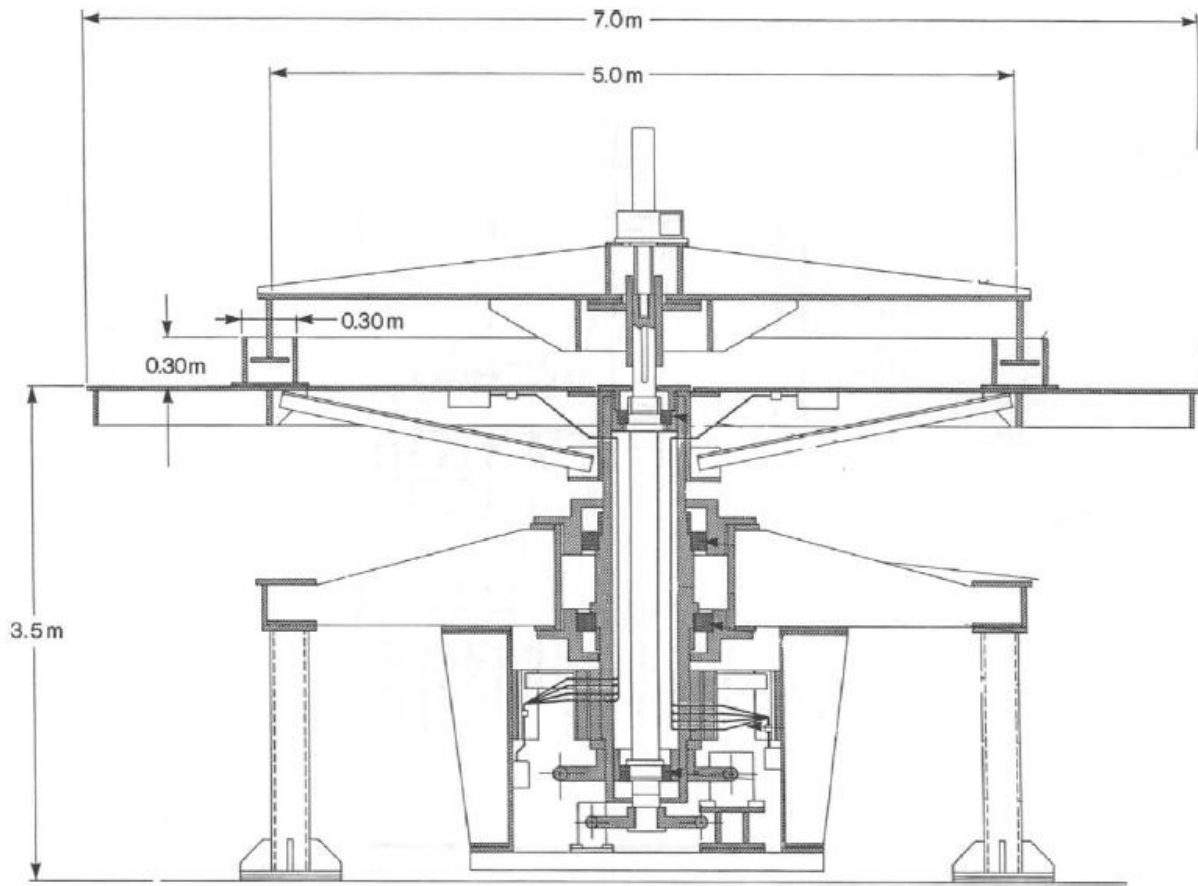


Figure D.2: Schematic representation of the rotating annular flume (Krishnappan, 2007)



Figure D.3: End of ingress experiment.



Figure D.4: End of ingress experiment after manual agitation of the gravel framework.



Figure D.5. Lambert and Walling (1998) method for fine sediment collection for the flume experiments.

Appendix E

Appendix E provides supplementary material regarding Chapter 6.

Mathematical description of the RIVFLOC Model.

Further details can be found in Krishnappan (2022)

1. *Transport and dispersion components of RIVFLOC*

The transport and dispersion processes are analyzed through a depth-averaged advection-dispersion equation expressed in the curvilinear coordinate system (following the general direction of the channel flow) introduced by Yotsukura and Sayre (1976). The curvilinear coordinate system is specified according to the detailed topographic survey conducted in the field.

$$\frac{\partial C_k}{\partial x} = \frac{\partial}{\partial \eta} \left(\frac{M_x U h^2 E_z}{Q^2} \frac{\partial C_k}{\partial \eta} \right) + \frac{M_x \lambda_1}{U} C_k + \frac{M_x}{U} \lambda_2 \quad (\text{Eq. E1})$$

where,

C_k = depth-averaged volumetric concentration of the k_{th} size fraction,

x = distance along the longitudinal co-ordinate axis,

U = depth-averaged velocity component in the x direction (determination of U are found in detail in Krishnappan (2022)).

h = depth of flow,

Q = flow rate,

E_z = transverse dispersion coefficient,

M_x, M_z = metric coefficients of the curvilinear co-ordinate system,

$\eta = \frac{1}{Q} \int_0^z M_z U h dz$ = normalized cumulative discharge,

z = transverse co-ordinate,

λ_1 = rate coefficient for reaction,

λ_2 = rate of sediment source or sink.

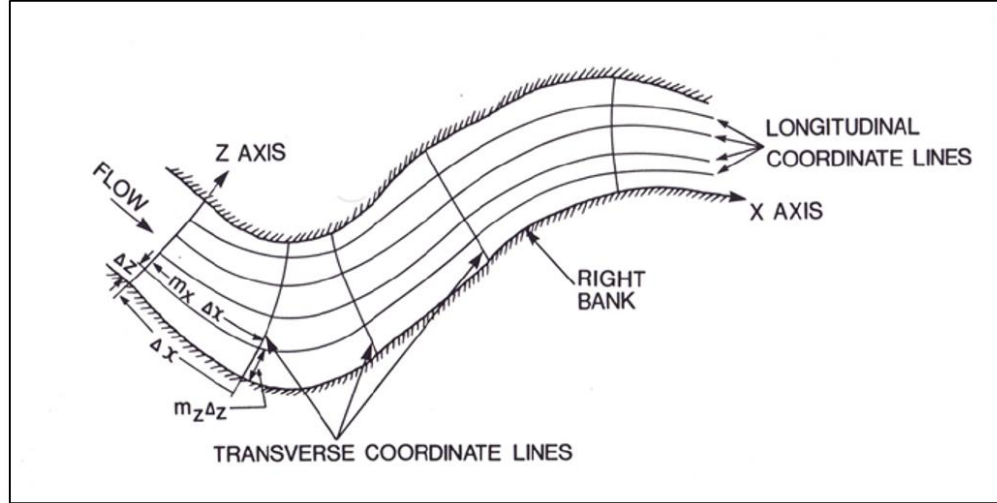


Figure E1: The curvilinear coordinate system used in the transport and dispersion component of the RIVFLOC model. Source: Krishnappan (2022)

The mass balance equation (Eq. S1) is solved using the following boundary conditions: i) The upstream boundary, which is the first upstream cross-section at which known values of TSS and ESPDs are specified as measured in the field; ii) The side banks, where concentration gradients are specified as zero, and; iii) The channel bed, where sediment fluxes between the channel bed and the water column are specified using the following equations describing fluxes of deposition (q_d , Eq. S2), ingress ($q_{ingress}$, Eq. S3), and erosion (q_e , Eq. S4):

Net deposition flux,

$$q_d = P w_s C_{kb} \quad (\text{Eq. E2})$$

where,

P is the probability that a floc will settle, $P = \left(1 - \frac{\tau}{\tau_{CrDK}}\right)$, for $\tau < \tau_{CrDK}$, and $P = 0$, for $\tau > \tau_{CrDK}$

w_s is the floc settling velocity,

C_{kb} is the near-bed concentration of the k th size fraction of the sediment,

Net ingress flux,

$$q_{ingress} = \alpha w_s C_{kb} \quad (\text{Eq. E3})$$

where,

α is the ingress coefficient.

Net erosion flux

$$q_e = E \quad (\text{Eq. E4})$$

where,

E is the erosion rate, $E = h \frac{1/c_1}{\left(\frac{c_0}{c_1}t + 1\right)^2}$, and c_0 and c_1 are empirically defined coefficients obtained through the flume experiment, and t is the time in which a certain applied shear stress is maintained in the flume.

2. Flocculation component

The flocculation component of RIVFLOC is calculated based on the simplification of the coagulation equation proposed by Fuchs (1964):

$$\frac{\Delta N_i}{\Delta t} = - \sum_{j \neq i} \beta K(r_i, r_j) N_i N_j + \sum_{j < i} f_{i,j} \beta K(r_i, r_j) N_i N_j + \sum_{j < i-1} (1-f_{i,j}) \beta K(r_i, r_j) N_{i-1} N_j \quad (\text{Eq. E5})$$

where,

N is the number of flocculated particles,

r_i and r_j are geometric mean radius of particles in discrete size ranges i and j ,

β is the cohesion factor, which defines the probability that a pair of collided particles will form

a new floc, and it was determined empirically through the flume experiments,

$$f_{i,j} \text{ is the allocation function, } f_{i,j} = \frac{(\rho_{f,i} V_i + \rho_{f,j} V_j - \rho_{f,j} V_{i+1})}{(\rho_{f,j} V_i - \rho_{f,j+1} V_{i+1})},$$

ρ_f is the density of the floc (Eq. 1),

V is the volume of the flocs,

$K(r_i, r_j)$ is the collision frequency function, which assumes different functional forms depending on the collision mechanisms. The considered mechanisms in RIVFLOC include Brownian motion (K_b), turbulent fluid shear (K_{sh}), inertia (K_l), and differential settling (K_{ds}):

$$K_b(r_i, r_j) = \frac{2}{3} \frac{KT}{\mu} \frac{(r_i - r_j)^2}{r_i r_j} \quad (\text{Eq. E6})$$

$$K_{sh}(r_i, r_j) = \frac{4}{3} \left(\frac{\varepsilon}{\nu} \right)^{1/2} (r_i - r_j)^3 \quad (\text{Eq. E7})$$

$$K_I(r_i, r_j) = 1.21 \left(\frac{\rho_f}{\rho} \right) \left(\frac{\varepsilon^3}{\nu^5} \right)^{1/4} (r_i + r_j)^2 |r_i^2 - r_j^2| \quad (\text{Eq. E8})$$

$$K_{ds}(r_i, r_j) = \frac{2}{9} \frac{\pi g}{\nu} \left(\frac{\rho_f - \rho}{\rho} \right) (r_i + r_j)^2 |r_i^2 - r_j^2| \quad (\text{Eq. E9})$$

where,

K is the Boltzmann constant,

T is the absolute temperature in degree kelvin,

μ is the viscosity of fluid,

ν is the kinematic viscosity of the fluid,

ε is the turbulent energy dissipation per unit mass

ρ_f is the density of the sediment,

ρ is the density of the fluid.

Accordingly, an effective collision frequency (K_{ef}) is calculated as:

$$K_{ef} = K_b + \sqrt{K_{sh}^2 + K_I^2 + K_{ds}^2} \quad (\text{Eq. E10})$$

The breakup of flocculated particles in RIVFLOC was calculated according to the method proposed by Tambo and Watanabe (1979), which introduces a collision-agglomeration (α_R) as a multiplier to K_{ef}, and is calculated as:

$$\alpha_R = \alpha_0 \left(1 - \frac{R}{(R_m + 1)} \right)^n \quad (\text{Eq. E11})$$

where,

R is the number of primary particles in a floc,

R_m is the number of particles in the largest floc for a given level of turbulence,

And parameters α₀ and n assume the values of 1/3 and 6, respectively, obtained empirically through the observations of Tambo and Watanabe (1979).



Figure E.2: Generally, the banks of the Crowsnet River are stable and well-vegetated. This figure shows an exception, which can act as a channel source of fine sediment.



Figure E.3: Submerged structure that can also favor sedimentation in the Crowsnest River.

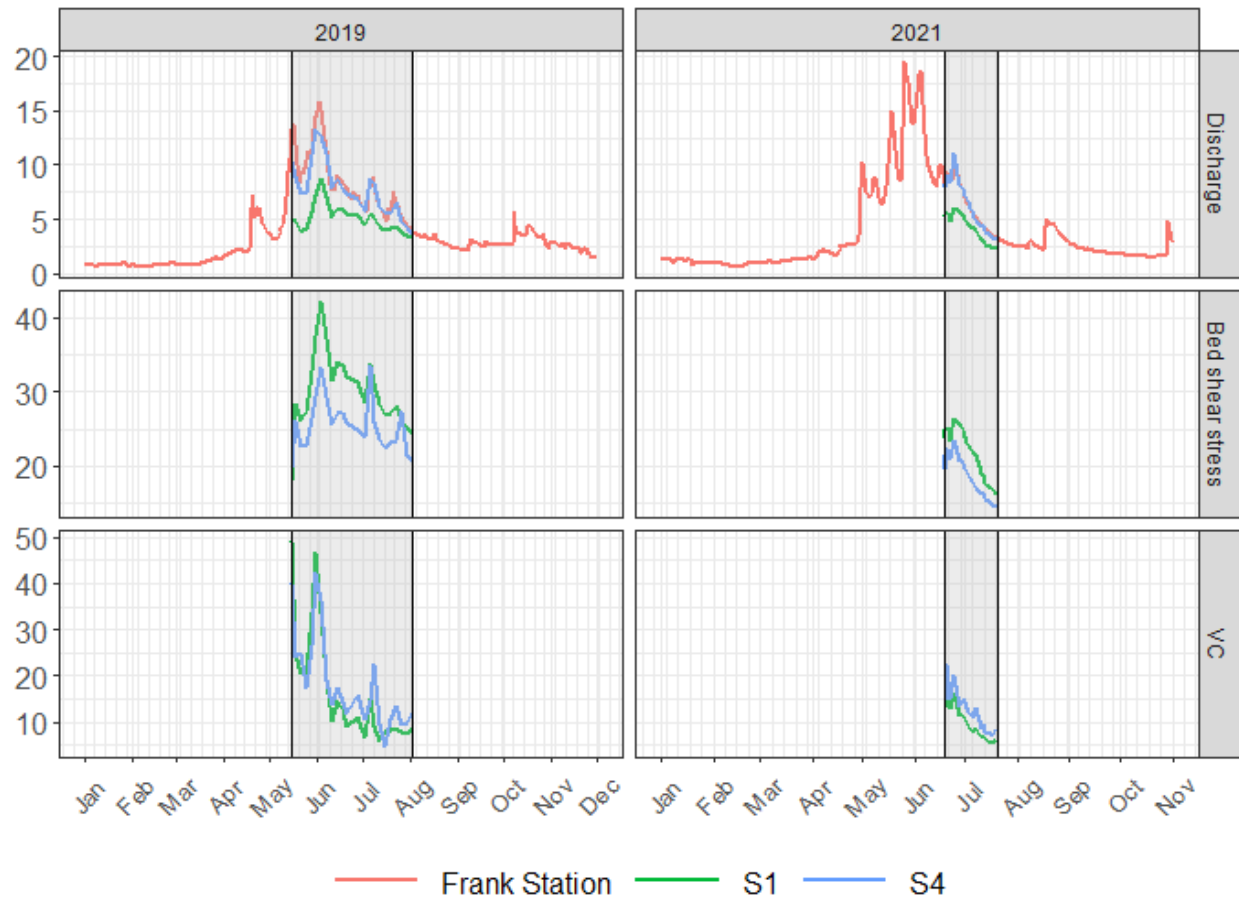


Figure E.4: Instantaneous discharge ($\text{m}^3 \text{s}^{-1}$), bed shear stress (N m^{-2}), and suspended sediment volume concentration (VC – $\mu\text{L L}^{-1}$) for the study dates on upstream and downstream sites.

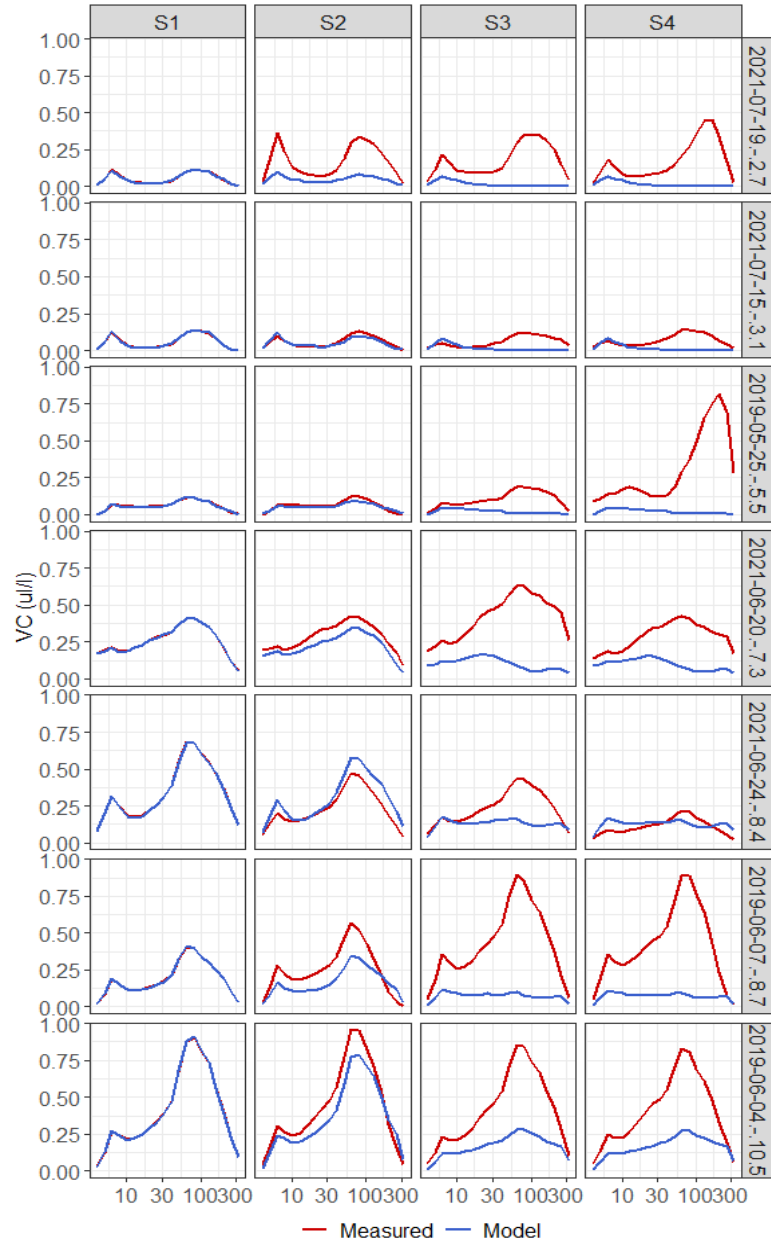


Figure E.5: Volume concentration (VC) of EPSDs modelled with RIVFLOC and measured *in-situ* for different dates (year-month-day) and discharge events ($\text{m}^3 \text{s}^{-1}$).

Glossary

Term	Definition
APSD	Absolute particles size distribution
A_w	Flow area
d	Flow depth
df	Degrees of freedom
D_w	Hydraulic depth
EPSD	Effective particle size distribution
f	Friction factor
Fr	Froude number
g	Acceleration of gravity
H	Horizontal ingress trap
HQ	Higher discharge event
HV	Horizontal-vertical ingress trap
LME	Linear mixed effects models
LQ	Lower discharge event
Q	Discharge
R²	Coefficient of determination
RSD	Relative standard deviation
RV	Relative volume concentration
SD	Standard deviation
SE	Standard error
SPM	Suspended particulate matter
T	Width of the flow

TSS	Total suspended solids
$\bar{u}$	Mean velocity
u^*	Shear velocity
V	Vertical ingress trap
VC	Volume concentration
α	Ingress coefficient
β	Cohesion factor
ρ	Density of the water
ρ_f	Density of the floc
ρ_p	Density of the parent material
τ	Shear stress
τ_0	Bed shear stress
τ_{CrDK}	Critical shear stress for deposition according to Krone
τ_{CrDP}	Critical shear stress for deposition according to Partheniades
τ_{CrE}	Critical shear stress for erosion
ϕ	Porosity
χ^2	Chi-squared test
ω_k	Settling velocity
ω	Unit shear stress