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# Hydro-sedimentological drivers of fine sediment ingress in a gravel-bed river

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ABSTRACT

Most studies investigating fine sediment ingress in gravel-bed rivers have been conducted at the laboratory scale, and even fewer have explored the ingress processes of flocculated particles. Here, an extensive *in-situ* sampling programme was undertaken to investigate hydro-sedimentological drivers of interstitial fine sediment accumulation and to evaluate fine sediment ingress directional mechanisms in a gravel-bed river located on the eastern slopes of the Rocky Mountains in southern Alberta. Three sediment trap designs were installed across seven deployment cycles at four sites along the river. Instantaneous discharge, suspended solids concentration, and particle size distributions (of suspended and ingressed particles) were measured, while relevant hydraulic parameters were modelled with a flow model (MOBED). Distinct patterns of ingress dynamics between non-cohesive and cohesive fractions of fine sediment were observed. While the assessed hydro-sedimentological parameters did not statistically explain the ingress rates of non-cohesive 0.5 – 2 mm particles, the opposite was observed for < 0.5 mm particles, which were mostly transported in flocculated form. For flocculated sediment, horizontal ingress accounted for ~ 60 % of interstitial accumulation. Directional ingress mechanisms, however, were dependent on flow conditions for both particle size fractions, with vertical and horizontal accumulations becoming more important during higher and lower energy flows, respectively. Our observations demonstrate the importance of ingress for the interstitial accumulation of fine sediment, even during events with flow above the critical threshold conditions for fine sediment gravitational deposition. Despite the comparable ingress rates to other studies, no interstitial clogging was observed in this study, demonstrating the channel potential storage capacity, which has implications for legacy impacts from landscape disturbances in the Crowsnest River catchment.

## 1. 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,

*Abbreviations:* EPSD, Effective particle size distribution; APSD, absolute particles size distribution; VC, volume concentration; HQ, higher discharge event; LQ, lower discharge event; TSS, total suspended solids; V, vertical ingress trap; H, horizontal ingress trap; HV, horizontal-vertical ingress trap.

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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.

## 2. Methods

### 2.1. Study site

The Crowsnest River is located on the eastern slopes of the Canadian Rocky Mountains in southwestern Alberta (Fig. 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$^{-1}$ (Fig. 1). The concentration of suspended solids (total suspended solids – TSS) in the Crowsnest River is normally < 5 mg/L during base flow but can exceed 100 mg/L during snow melt and stormflow conditions (Maltauro et al., 2023b; 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 (Fig. 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 1, Fig. 1). All gravel bars remained submerged throughout the sampling period.

### 2.2. 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; Fig. 1) to estimate discharge at sites 2 and 3 (Fig. 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; Supplementary material Fig. S1). 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

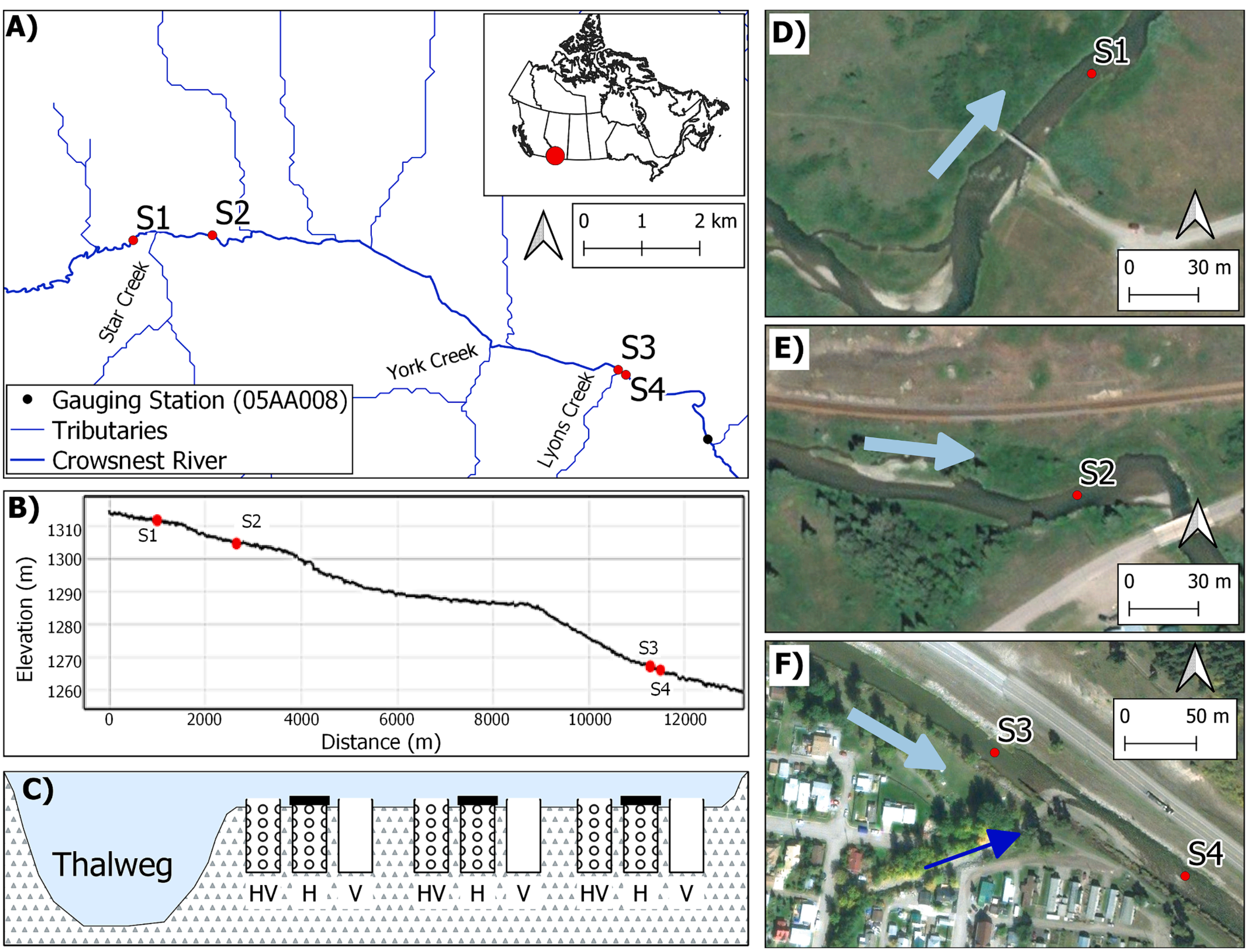


**Fig. 1.** A) Location map; B) elevation map obtained with river channel topographic survey; C) schematics for sediment trap deployment, which was replicated at the four sites; D, E and F) Location of each gravel bar in relation to the closest upstream bend (lighter blue arrows over imagery indicate the flow direction in the Crowsnest River, darker blue arrows indicate flow direction in Lyons Creek).

**Table 1**
Characteristics of the studied gravel bars and summary of observed flow conditions.

| | *Site 1* | | *Site 2* | | *Site 3* | | *Site 4* | |
|---|---|---|---|---|---|---|---|---|
| *Bed slope* | ~ 0.003 m/m | | ~ 0.005 m/m | | ~ 0.006 m/m | | ~ 0.006 m/m | |
| *Location within the gravel bar* | ~ 70 m downstream of a bend | | ~ 10 m downstream of a bend | | ~ 100 m downstream of a bend | | ~ 100 m downstream of tributary confluence | |
| $D_{10\ gravel}$ *(mm)* | 12 | | 12 | | 35 | | 19 | |
| $D_{50\ gravel}$ *(mm)* | 24 | | 41 | | 82 | | 70 | |
| $D_{90\ gravel}$ *(mm)* | 54 | | 95 | | 140 | | 220 | |
| $\phi_{gravel}$ *(%, mean ± s.d.)* | 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 |
| *VC (ppm)* | 10.0 | 5.5–20.8 | 10.0 | 5.2–19.3 | 14.0 | 6.7–27.9 | 12.4 | 7.1–22.5 |
| *TSS* $(mg\ l^{-1})$ | 4.2 | 0.0–11.6 | 5.2 | 1.8–11.2 | 4.1 | 0.0–14.9 | 5.0 | 1.9–13.1 |
| *Q* $(m^3\ s^{-1})$ | 4.2 | 2.2–6.0 | 4.5 | 2.3–6.6 | 5.9 | 3.0–10.0 | 6.4 | 3.2–11.1 |
| *d (m)* | 0.6 | 0.5–0.8 | 0.6 | 0.4–0.8 | 0.7 | 0.5–0.9 | 0.6 | 0.4–0.9 |
| *Fr* | 0.3 | 0.3–0.6 | 1.0 | 0.7–1.8 | 0.6 | 0.5–0.9 | 0.7 | 0.5–1.1 |
| $\tau_0$ *(Pa)* | 21.6 | 16.3–26.3 | 18.0 | 13.2–21.9 | 20.5 | 15.7–26.2 | 18.6 | 14.4–27.0 |
| $\omega$ $(W\ m^{-2})$ | 15.1 | 8.5–20.9 | 34.2 | 24.6–50.3 | 24.3 | 15.0–35.6 | 26.2 | 15.8–39.4 |

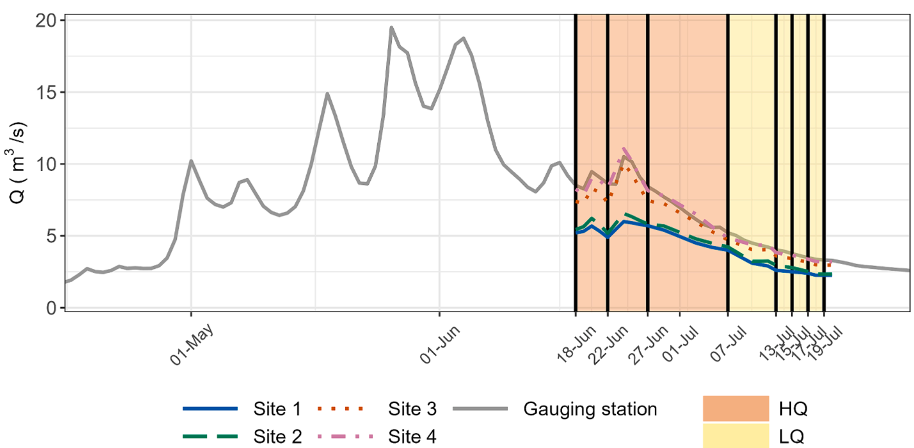


**Fig. 2.** Measured discharge at the study sites in relation to discharge in the Crowsnest River at the Frank gauging station (05AA008). Vertical lines indicate the time delimitation of each ingress trap deployment cycle.

through a calibrated flow model (MOBED; discussed below) (Krishnappan, 1981). Fine sediment ingress was measured using sediment ingress traps deployed over seven cycles (Fig. 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).

### 2.3. Assessment of fine sediment ingress

Fine sediment ingress mechanisms were assessed through the deployment of three types of ingress traps (Fig. 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) (Fig. 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 kg $day^{-1}$ $m^{-2}$ (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), $\rho_w$ is the density of water (1 g $cm^{-3}$), $m_g$ is the mass of gravel (g), and $\rho_g$ is the density of the gravel (2.6 g $cm^{-3}$).

While sieve-washing accumulated sediment < 0.5 mm, samples of ~ 3 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 μm) 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 (Relative VC $= VC_{\text{size class}}/\text{Total } VC_{<500\,\mu m}$).

### 2.4. 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., 2021). 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 ~ 20 m (Fig. 1B), and cross-sectional geometry was measured every ~ 500 m along the ~ 10 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 ($\tau_0$), unit stream power ($\omega$), and Froude number (Fr) daily during the study period at the four study sites. Bed shear stresses (Pa) were calculated as:

$$\tau_0 = u^{*2} \times \rho_w \tag{2}$$

$$u^* = \frac{\overline{u}}{f} \tag{3}$$

$$\overline{u} = \frac{Q}{A_w} \tag{4}$$

where $\rho_w$ is the water density (1000 km $m^{-3}$), $u^*$ is the shear velocity (m/s) and $\overline{u}$ is the mean velocity (m/s). Unit stream power ($W/s^{-2}$(−|-)) was calculated as:

$$\omega = \tau_0.\overline{u} \tag{5}$$

Froude numbers were calculated as:

$$Fr = \frac{\overline{u}}{\sqrt{g.D_w}} \tag{6}$$

$$D_w = \frac{A_w}{T} \tag{7}$$

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.

### 2.5. 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 mm and 0.5 – 2 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 mm particles. Since LME results regarding the 0.5 – 2 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 $\chi 2$ 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.

## 3. Results

Total ingress rates (<2 mm) in the Crowsnest River were 0.005 ± 0.003 (average ± SE) kg $day^{-1}$, ranging from 0.0012 to 0.0207 kg $day^{-1}$ (HV traps, Fig. 3), and ingress rates per accumulation area (V traps) were 0.44 ± 0.32 (average ± 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 (Fig. 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 (Supplementary material Fig. S2 and S3).

The assessment of APSDs and EPSDs demonstrated that particles < 0.5 mm were consistently flocculated regarding suspended ($D_{50\ EPSD} =$ 54.5 μm and $D_{50\ APSD} = 18.6$ μm) and ingressed ($D_{50\ EPSD} = 59.4$ μm and $D_{50\ APSD} = 14.4$ μm) sediment (Fig. 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 μm (Fig. 3B), flocculated particles were predominantly within effective size classes of 9 – 67, and 67 – 130 μm (Fig. 3C). The relative VC of dispersed particles > 67 μm corresponded to only ~ 14 % of all sediment < 0.5 mm (Fig. 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 ($p < 0.001$) (Supplementary material Fig. S4).

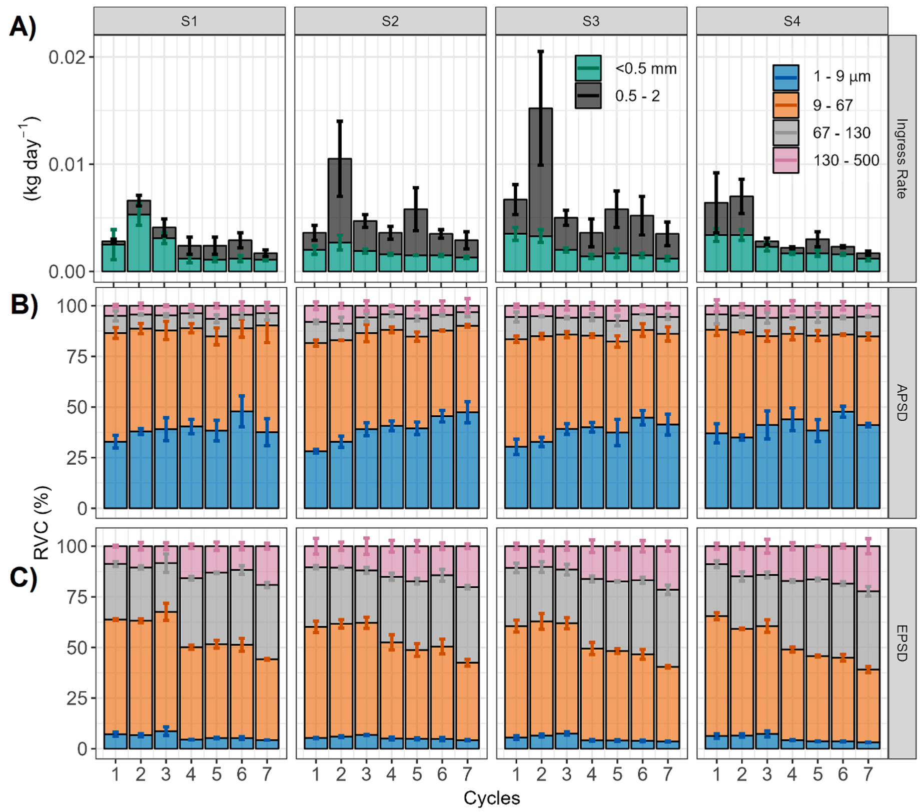


**Fig. 3.** Mean ± SD of A) ingress rates, B) relative volume concentration (RVC) for absolute particle size distributions (APSDs), and C) RVC for effective particle size distributions (EPSDs) using HV sediment traps.

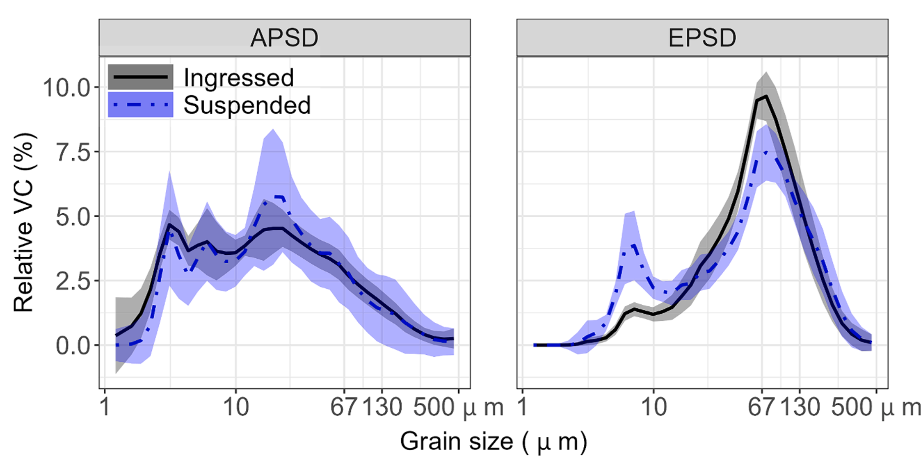


**Fig. 4.** Absolute and effective particle size distributions of ingressed (measured on HV traps) and suspended sediment. Lines represent median of all measurements ($n_{suspended}$ = 112, $n_{ingressed}$ = 84 for each absolute and effective distributions), and shaded areas represent ± 1SD.

Higher variability in ingress rates was observed regarding the 0.5 – 2 mm size class (Fig. 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 2). In regards to the < 0.5 mm size class, which mostly consisted of flocculated particles, the interaction between ingress directional mechanisms and the parameters VC, $\tau_0$, and ω, presented conditional $R^2 > 70$ % (models assessing TSS, Q, and water depth presented conditional $R^2 > 60$ %) (Table 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 2).

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 (Fig. 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 (Fig. 5). Linear regressions performed for particles < 0.5 mm showed positive correlations between hydro-sedimentological drivers and ingress rates for both mechanisms (Fig. 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 (Fig. 6). Positive relationships between ingress rates of finer and coarser fractions of fine

**Table 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 | | | |
|---|---|---|---|---|---|---|---|---|
| | $\chi^2$ | p-value | $R^2$ | | $\chi^2$ | 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 |
| $\tau_0$ | 351.36 | < **0.001** | m | 0.637 | 0.59 | 0.441 | m | 0.003 |
| $\tau_0$: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 |

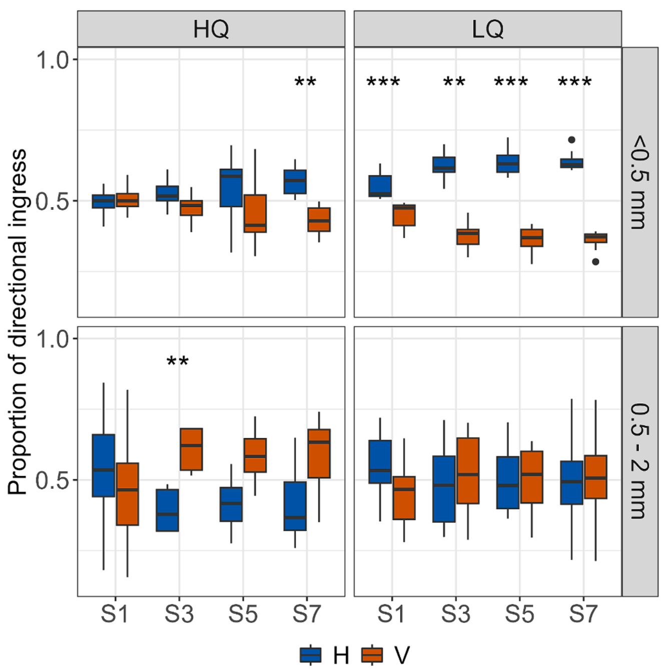


**Fig. 5.** Wilcoxon signed rank test pairwise comparison between ingress mechanisms (n = 9 for each design of ingress trap during HQ, n = 12 for each design of ingress trap during LQ). Proportions indicate H + V = 1. Adjusted (Benjamini-Hochberg) p-values: **p < 0.01, and ***p<0.001. Median, upper, and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range.

sediment were observed for sites 2, 3 and 4, but the corresponding $R^2$ were all < 40 % (Fig. 7).

## 4. Discussion

### *4.1. 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 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). Casas-Mullet et al. (2017) assessed total fine sediment ingress < 2 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-Mulet 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 (~0.15 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 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., 2023a), can further corroborate the poor relationships observed in the LME models for the 0.5 – 2 mm size class.

Conversely, the LME results showed that most of the assessed parameters (except by Froude number; Table 2 and Fig. 6) were important in controlling ingress rates of the < 0.5 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 mm size class showed that both flow related parameters (Q, d, $\tau_0$ 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., 2023b; 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

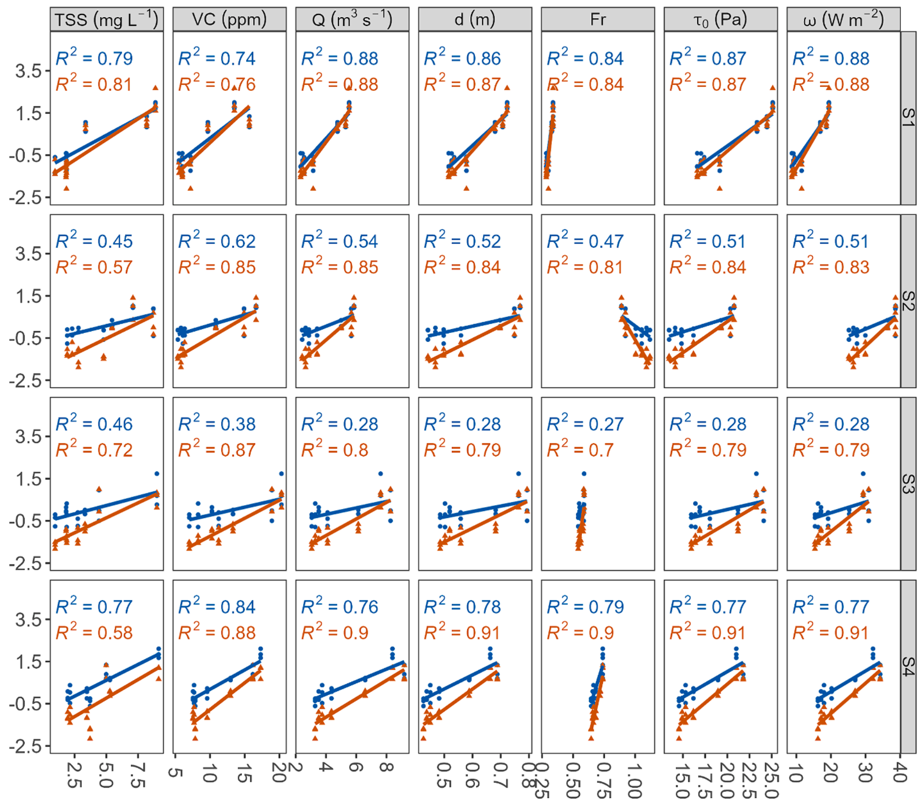


**Fig. 6.** Linear regressions of normalized ingress rates as a function of hydro-sedimentological parameters for the < 0.5 mm size class for different ingress mechanisms. Normalized ingress rates in the y-axis, blue dots and orange triangles indicate data from H and V traps, respectively. All p-values < 0.05.

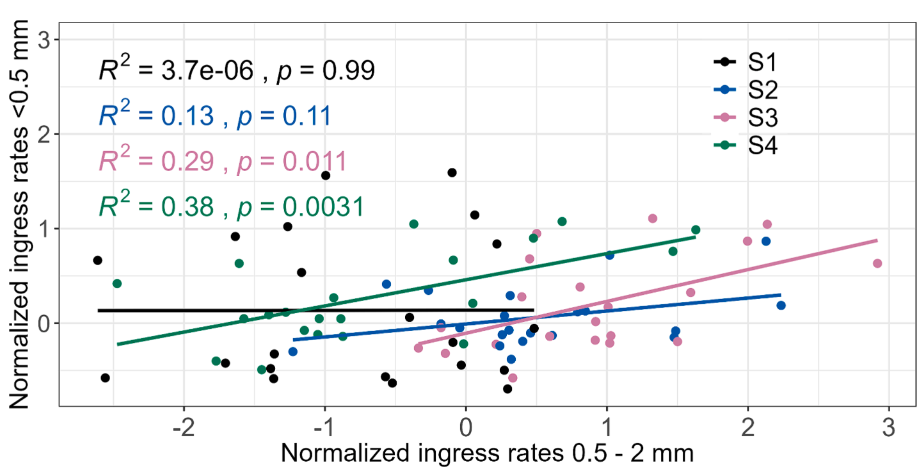


**Fig. 7.** Relationships between ingress rates of coarser and finer size classes. Measurements from HV ingress traps.

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., 2023b). 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 (Fig. 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 (Supplementary material Fig. S3), 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 2, Fig. 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.

### 4.2. 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 ~ 58 % when considering particles < 0.5 mm and ~ 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 ~ 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 (Fig. 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 (~2.6 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 (Fig. 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, Fig. 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.

### 4.3. 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 if 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 $d_{15framework}/d_{85sediment}$ 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 streamed 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, 2007; 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.

## 5. 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.

## CRediT authorship contribution statement

**R. Maltauro:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **M. Stone:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing – review & editing. **A.L. Collins:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **B.G. Krishnappan:** Methodology, Resources, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mike Stone reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Adrian L. Collins reports financial support was provided by UK Research and Innovation-Biotechnology and Biological Sciences Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2024.108067.

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