The gravel-sand transition and grain size gap in river bed sediments

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Abstract

River bed sediments typically fine downstream, where fining of median grain sizes are often described as exponential, except where fine gravel abruptly transitions to sand. Across the gravel-sand transition, median grain sizes can reduce by more than 10 mm (>90%) over a distance of only a few channel widths. There are several viable theories for why the gravel-sand transition occurs, but they remain a matter of ongoing discussion in the literature. Here, we present a review of known morphological characteristics associated with gravel-sand transitions and the existing theories for their development (e.g., abrasion, size selective transport, washload deposition). This is combined with a global database of published gravel-sand transitions across a range of climatic, tectonic and geographic settings. We identify an absence of universal morphological characteristics associated with the transition. However, the position of the transition is relatively predictable, occurring either a small distance downstream of mountain ranges or at a characteristic backwater distance upstream of a base-level control. This supports previous findings where the position of the transition is sensitive to long-term changes in gravel runout distance (e.g., through changes in gravel supply, basin subsidence rate) and/or changes in base level (e.g. sea level rise). Both backwater effects and exhaustion of gravel supply generate a distinct and abrupt change in water surface slope between the gravel and sand reaches, suggesting this is a control on the location at which they develop. The abrupt nature of the gravel-sand transition is then considered in terms of the two theories that seem most able to explain the phenomenon at the granular scale. We also focus on the apparent absence of river beds with median bed grain diameters of ~1-10 mm, or within the 'grain size gap', to better understand how this relates to the development and nature of gravel-sand transitions. The absence of median bed grain sizes within this range may be a reflection of grain size statistics, where these grain sizes are actually present but never dominate bed material. Alternatively, these grain sizes may be absent from hillslope sediment sources. Finally, we consider how particle dynamics may prevent formation of a stable gravel bed with gap material. Even if these grain sizes are produced on hillslopes, particles may raft downstream over the sand bed and disperse. Research into how grain size gap material is generated, transported and deposited in river systems should be a future priority.

Keywords: Gravel-sand transition, grain size, abrasion, sediment transport, washload

1. Introduction

Rivers draining mountain ranges transport large quantities of sediment, most of which is eventually delivered to the ocean. As sediment is carried downstream by rivers, particles that characterize the channel bed surface evolve, getting finer in the absence of lateral inputs of material from hillslopes or tributaries. This pattern has been well documented in natural river systems and grain size fining is typically described as exponential (e.g., Sternberg, 1875; Yatsu, 1955; Paola et al., 1992a; Sambrook-Smith and Ferguson, 1995; Rice, 1999). The rate of downstream fining depends on a combination of the mechanical breakdown of particles (abrasion), and size selective transport, in which clast size is conserved and downstream fining occurs as flow competence decreases towards base level (e.g., Yatsu, 1955; Paola et al., 1992a). Once the surface median grain size reduces to ~10 mm, there is an abrupt transition to a sand bed with a median grain size of ~1 mm (Shaw and Kellerhals, 1982; Ferguson et al., 1996). At this point, the bed structure also changes from framework- to matrix-supported (Sambrook Smith and Ferguson, 1995; Frings, 2011; Venditti and Church, 2014). This abrupt transition in median grain size, termed the gravel-sand transition, can occur over a distance as little as a few tens or hundred meters (or a couple of channel widths equivalent) and is often associated with a break in water surface slope (Yatsu, 1955; Shaw and Kellerhals, 1982; Sambrook-Smith and Ferguson, 1995; Frings, 2011; Venditti and Church, 2014). This is the only abrupt grain size reduction in the fluvial system. Interestingly, there is a general absence of river bed surfaces characterized by median grain sizes between ~1 and 5 mm (Lamb and Venditti, 2016), a range in grain size which we refer to as the 'grain size gap'. At larger scales, the gravel-sand transition denotes a boundary between distinct river planforms and channel morphologies (e.g., Labbe et al., 2011; Dingle et al., 2020) and represents a change between different types of depositional architecture in sedimentary basins (e.g., Paola et al., 1992b, Robinson and Slingerland, 1998; Marr et al., 2000; Dubille and Lavé, 2015). Whether the transition is externally imposed, a result of internal dynamics (i.e. an emergent property), or some other combination of sediment sorting and abrasion processes, is a matter of ongoing discussion in the literature.

The objective of this review is to evaluate our current understanding of gravel-sand transitions in terms of both their morphology and possible causal mechanisms. We outline known characteristics associated with gravel-sand transitions (e.g. length, channel mobility, change in grain size) and using detailed measurements of channel planform and geometry of five river systems, we consider environmental factors that may influence these characteristics and associated morphological change on a case-by-case basis. The main existing theories that have been proposed to explain their formation are then discussed and critiqued. We present a global database of gravel-sand transitions across a wider range of geographical, tectonic and climatic settings. Using this global database, we identify particular commonalities in the location of gravel-sand transitions. This highlights specific causal mechanisms or conditions that may be required for gravel-sand transition formation. Finally, we discuss possible causes of the grain size gap in river bed sediments in terms of preferential abrasion, hillslope supply, particle mobility and transport mode separation.

2. Nature of the gravel-sand transition in river systems

Existing research on the development of gravel-sand transitions has been built around physical experiments (e.g., Paola et al., 1992a; Seal et al., 1997; Sambrook-Smith and Ferguson, 1996), analytical and numerical models (e.g., Cui and Parker, 1998; Parker and Cui, 1998; Blom et al., 2017) and direct field observations (e.g., Shaw and Kellerhals, 1982; Ferguson et al., 1996; Singer et al., 2010; Venditti and Church, 2014). Ongoing challenges include difficulty in obtaining direct measurements of fluid and sediment dynamics across multiple flow stages (e.g., Venditti et al., 2015; Dingle et al., 2020), and downscaling of properties that may be specific to gravel and sand grain sizes in physical experiments (Paola et al., 2009). As such, the number of well-documented field examples is quite limited. Where observations do exist, they encompass a broad geographical range (Figure 1) that reveal some common, although not strictly universal, morphological characteristics.

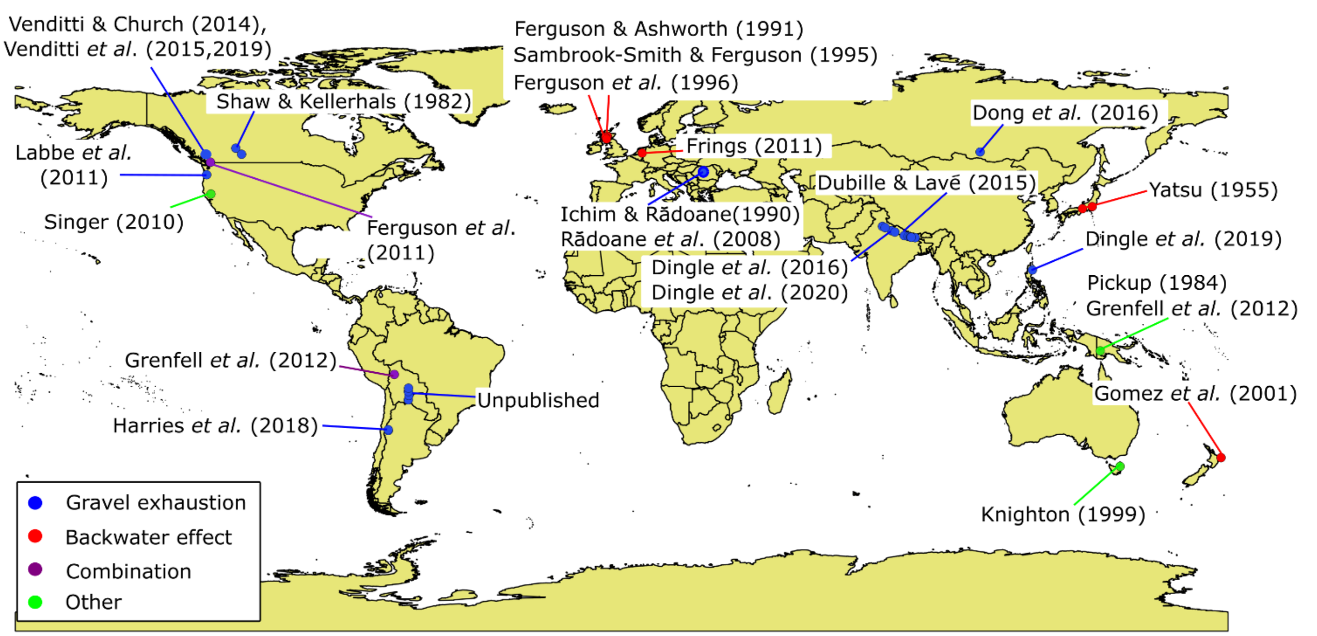

Figure 1. Location of previously published gravel-sand transitions (see Table 1 for details).

2.1 Grain size and grain size distributions

The gravel-sand transition is unusual in that the reduction in the median bed grain diameter (D_{50}) is more abrupt than typical fining rates found in river bed sediment (Sternberg, 1875; Sambrook-Smith and Ferguson, 1995). Coarse particle sizes (D_{90}; represented by the 90th percentile of the distribution) also rapidly fine across the gravel-sand transition while the fine material (D_{10}; 10th percentile) fines more gradually (Figure 2), reflecting the loss of the coarsest material or gravel mode from the distribution, as opposed to a self-similar fining mechanism. The D_{50} at the upstream limit of the transition varies between rivers, ranging from 67 mm to a minimum of ~5-6 mm (Table 1), but typically occurs at ~10 mm. The bed surface then rapidly transitions to sand (typically D_{50} ~ 1 mm) (Shaw and Kellerhals, 1982; Ferguson et al., 1996). Grain size distributions immediately upstream of the gravel-sand transition are often described as bimodal, with distinct sand and gravel populations (Sambrook-Smith and Ferguson, 1995; Venditti and Church, 2014). One commonality identified by Miller et al. (2014a) across a variety of field measurements and experimental alluvial fan experiments was this presence of a bimodal grain size distribution immediately upstream of the transition. They suggested that the dynamics controlling sand deposition at the gravel-sand transition are scale independent and insensitive to local hydraulics, topography and particle size.

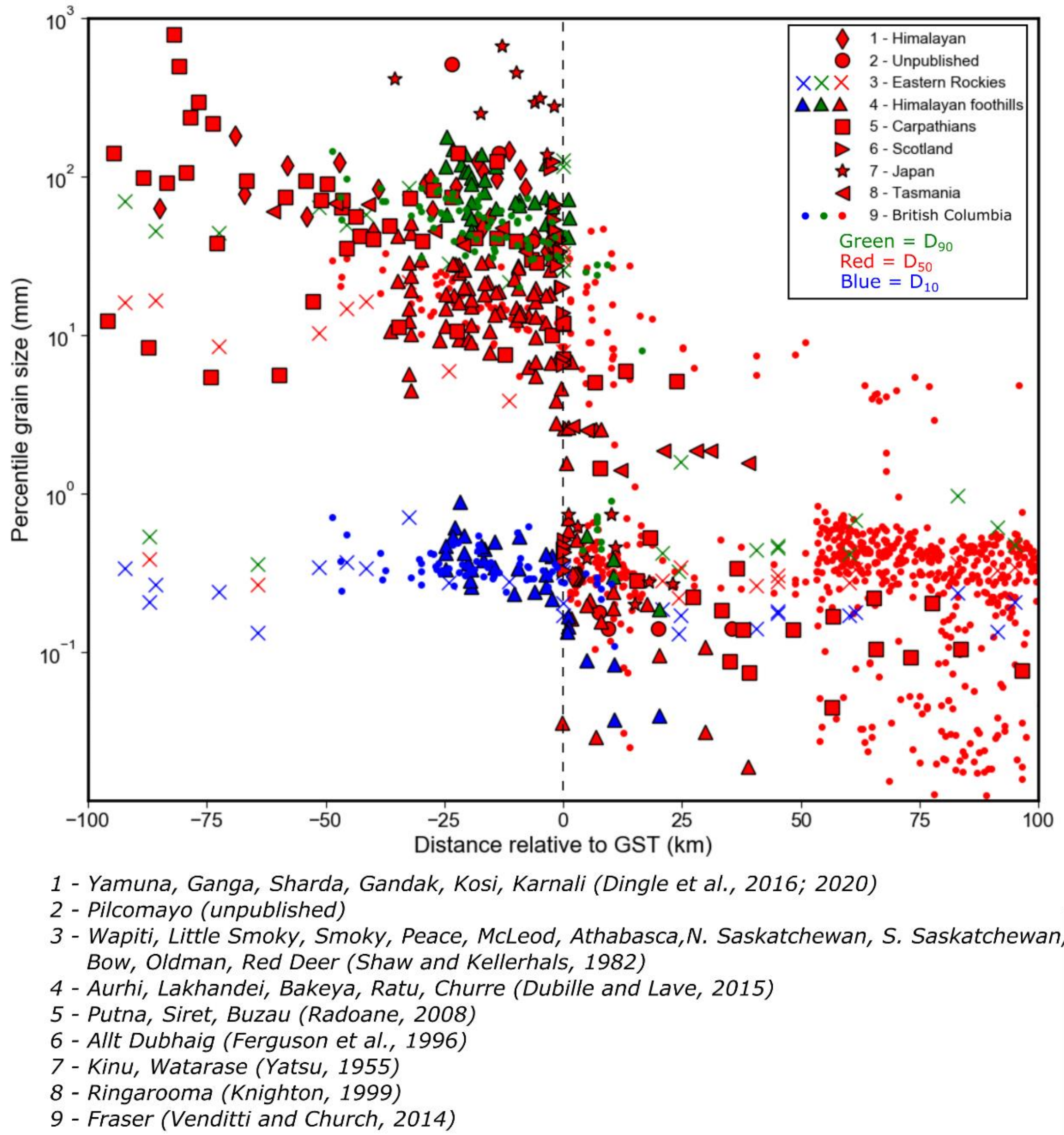

Figure 2. Percentile grain size change in bed surface sediments across a compilation of gravel-sand transitions. Markers in red are median (D_{50}) statistics, blue are D_{10} and green are D_{90}. Distances are plotted relative to the inferred position of the gravel-sand transition (GST), where negative values are upstream (flow direction is left to right).

In contrast, grain size distributions taken from the Red Deer and North Saskatchewan Rivers (Shaw and Kellerhals, 1982) show that the degree of bimodality immediately upstream of the transition may vary between systems (Figure 3). On approaching the gravel-sand transition, grain size distributions on the North Saskatchewan River were strongly bimodal, with two modes at ~0.3 and 25 mm at site 29. A further 20 km downstream at site 30, the bed surface was a unimodal sand bed (mode of ~0.3 mm). On the Red Deer River, the degree of bimodality was weaker. At site 13, a weakly bimodal grain size distribution with a primary mode of ~24 mm and secondary mode of ~0.2 mm was observed. The next sample (site 14), ~20 km downstream, briefly transitioned to sand bed conditions. Gravel-bed conditions returned, but with weaker bimodal or unimodal distributions (sites 15, 16 and 17). At site 18, a weakly bimodal distribution was observed but with the primary mode at ~0.3 mm (i.e. a sand bed channel with a small quantity of gravel), suggesting this sample was within a diffuse extension (see section 2.2) of the gravel-sand transition. At site 19 (~20 km further downstream), a unimodal sand bed channel was observed again.

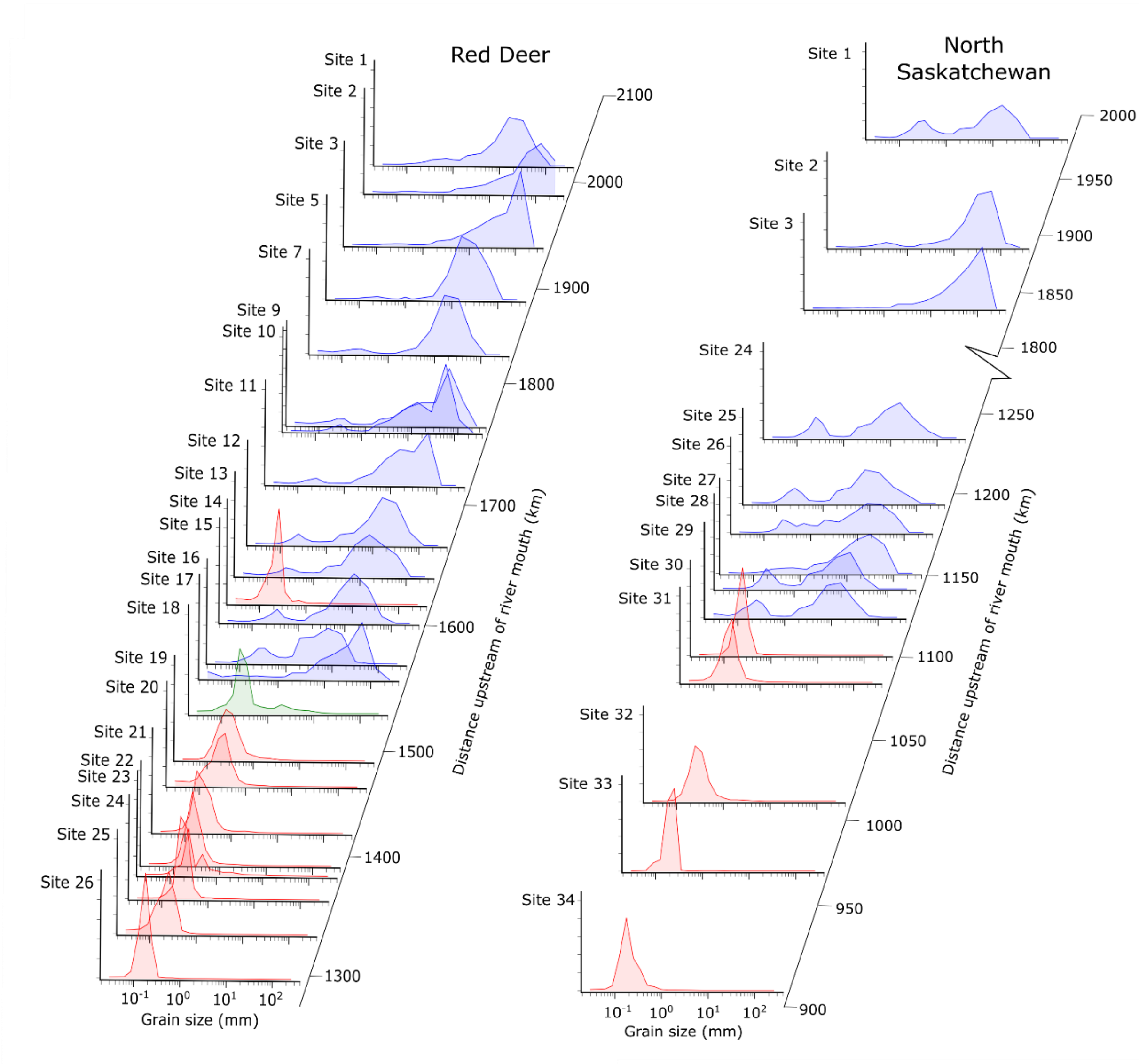

Figure 3. Grain size distributions plotted as a function of downstream distance for the Red Deer and North Saskatchewan Rivers, original data from Shaw and Kellerhals (1982). The y-axis represents the percentage of each grain size fraction retained. Distributions shown in blue are for gravel-bed samples and red for sand-bed samples. Sample 18 on the Red Deer is shown in green as was likely collected within a diffuse extension of the gravel-sand transition.

2.2 Length and the diffuse extension

Large lateral inputs of sediment from tributaries, dune sorting, and large-scale bend sorting processes that are more commonly seen in larger channels are also thought to influence sediment mobility and distance over which the gravel-sand transition extends (Frings, 2011). Variability in bed topography such as large-scale bar-pool complexes may also influence the length of the transition, although this cannot be assessed in small channels or flumes where the topographic variability is limited (Venditti and Church, 2014).

Studies of small river channels and flume experiments describe the transition as occurring over a distance equivalent to only a few channel widths (e.g., Paola et al., 1992a; Sambrook Smith and Ferguson, 1995). In larger basins, the length of the gravel-sand transition is usually greater, and a relation between channel size and transition length has previously been proposed (Frings, 2011). While the transition from a framework-supported gravel bed to a matrix-supported sand bed should be abrupt, surface deposits may be more complex. The Fraser River (British Columbia) has been described as a terminating gravel wedge with a diffuse extension, where small patches of gravel persist for 15-20 km (equivalent to 15 to 20 channel widths) downstream of the abrupt transition on a matrix-supported sand bed (Venditti and Church, 2014) (Figure 1). In many cases, the gravel-sand transition has been described as a 'zone' rather than a discrete location, where isolated patches of gravel on the sand bed persist for a couple of kilometers (e.g., Dingle et al., 2016), suggesting the presence of a diffuse extension may be more common than previously acknowledged. Gravel is transported through the diffuse extension by rafting over the sand bed due to the superior mobility of gravel (Jackson and Beschta, 1984; Ikeda, 1984; Iseya and Ikeda, 1987; Wilcock, 1998; Wilcock and McArdell, 1993; Wilcock and McArdell, 1997; Wilcock et al., 2001; Wilcock and Kenworthy, 2002; Wilcock and Crowe, 2003; Curran and Wilcock, 2005). Small quantities of gravel may overtake the gravel front as a result of downstream migration of the transition (e.g., Ylla Arbos et al., 2021) or simply due to higher flow conditions that temporarily enhance gravel mobility through the diffuse extension, with no long-term change in the position of the transition. The Sacramento River (California) changes from a gravel to sand bed system over a distance of over 175 km, corresponding to ~1500 channel widths (Singer, 2010) due to anthropogenic influences that restrict gravel supply, but not sand, and a decline in flood flows. This leads to sand deposition over a framework-supported gravel bed.

2.3 Changes in channel morphology and dynamics

An abrupt break in channel slope is one of the more commonly observed features across gravel-sand transitions (Sambrook-Smith and Ferguson, 1995). Sand reach gradients can be less than a tenth of gravel reaches (e.g., the Alt Dubhaig gradient decreases from 0.0022 to 0.0002; Table 1). In instances where the break in slope is more subdued or not distinguishable, studies have suggested the sand transport reaches capacity or that the sand load is so great that it overwhelms the gravel load, and effectively buries the small quantity of gravel still in transport (Wilcock, 1998; Cui and Parker, 1998; Dubille and Lavé, 2015). In well-documented cases of a diffuse extension downstream of the gravel-sand transition (e.g., the Fraser River; Venditti and Church, 2014), patches of gravel persist on a largely sand bed, or flow stage dependent bodies of sand temporarily settle on a gravel bed. The average gradient of the diffuse extension lies between that of the adjacent gravel and sand reaches (Venditti and Church, 2014), which may subdue the apparent break in slope between the gravel and sand reaches. Similar observations were made on the Rhine River by Ylla Arbos et al. (2011), where the change in gradient associated with the gravel-sand transition has reduced over the last ~23 years. This was attributed to enhanced mobility of fine gravel in the presence of sand, resulting in a more subdued break in slope.

Changes in channel planform from a braided morphology to a single thread meandering channel have also been noted across several gravel-sand transitions (e.g., Dubille and Lavé, 2015). Gravel reaches are often described as anabranching (braided, multithread, wandering) (Sambrook-Smith and Ferguson, 1995; Venditti and Church, 2014). Downstream of the transition, the channel often evolves into a single thread sand bed channel that may be actively meandering or stationary (Dubille and Lavé, 2015; Frings, 2011). Bars in the sand reach are usually more permanent, marked by vegetative cover (Sambrook-Smith and Ferguson, 1995).

Other changes noted across the gravel-sand transition include channel width and lateral channel migration rate (e.g., Labbe et al., 2011; Dingle et al., 2020), which relate to changes in bank sediment grain size and cohesivity. A 10-km reach capturing the gravel-sand transition in the Upper Tualatin River (Oregon Coast Range) was found to exhibit a concurrent reduction in channel slope, bed grain size and width-to-depth ratio where channels transitioned from a relatively sinuous gravel-bed channel to a narrower, deeper and less sinuous sand-bed channel (Labbe et al., 2011). These changes were attributed to a greater proportion of silt and clay size particles in the banks of the sand-bed channel, promoting increased bank strength and lateral stability of the channel. Riparian vegetation showed little variation between the gravel and sand reaches (Labbe et al., 2011), suggesting the grain size of the bank material was key in determining bank stability. In comparison, an increase in channel mobility was noted on the Karnali River (Nepal) across the gravel-sand transition (Dingle et al., 2020). The gravel-bed reach was characterized by a higher gradient, multi-thread channel where channel migration was controlled by channel avulsion (10^2 to 10^3 year frequency). In contrast, the sand reach was lower gradient, had fewer threads and channel migration was dominated by lateral bank erosion, where banks were found to migrate up to several hundred meters per year (Dingle et al., 2020). Unlike the Upper Tualatin River, the Karnali River had relatively stable gravel banks but unstable sand banks. The sand banks were notably devoid of silt and clay sized sediments, and therefore lack the cohesivity that was observed on the Upper Tualatin River. The grain size of sediment being transported through the gravel reach, and then subsequently deposited either within the channel or as an overbank deposit in the sand reach appears to, at least partially, condition the wider morphological response across the gravel-sand transition.

Table 1. Slope, grain size and planform changes through the gravel-sand transition in various rivers. Entries in bold are examined in more detail in Figure 3.

Source	*River*	*Location*	*Median Grain Size Before/After (mm)*	*Distance between grain size samples (km)*	*Slope Before /After GST*	*Climate zone**	*Planform information*	*Inferred cause of transition*
Yatsu (1955)	Sho	Japan	27.0 / 1.8	5	0.0020 / 0.0005	Cfa	Not specified	Backwater induced from coast (~4 km upstream of coastline)
	Nagara	Japan	25.0 / 1.1	2	0.0005 / 0.0002	Cfa	Not specified	Backwater induced from coast or dam (~35/40 km downstream)
	Kiso	**Japan**	**37.0 / 0.6**	**1**	**0.0010 / 0.0002**	**Cfa**	**Not specified**	**Backwater induced from coast or dam (~40 km upstream of coastline) or dam (~17 km downstream).**
	Kinu	Japan	17.0 / 0.9	5	0.0015 / 0.0008	Cfa	Not specified	Possibly backwater induced from coast (~50 km upstream of coastline).
	Watarase	Japan	28.0 / 0.7	2	0.0010 / 0.0006	Cfa	Not specified	
Ferguson and Ashworth (1991), Ferguson et al. (1996) Sambrook-Smith and Ferguson (1995)	Alt Dubhaig	Scotland	14.6 / 0.5	0.25	0.0022 / 0.0002	Cfc	Channel width in gravel reach is ~9-25 m, generally decreasing downstream. Evolves from steeper mildly braided to lower gradient active meandering planform, with no clear change related to the gravel-sand transition.	Backwater induced from an alluvial fan/dam**

	Endrick Water	Scotland	6.6 / 0.6	1	0.00016 / 0.00003	Cfa	Channel is ~ 25 m wide. Channel is actively meandering through the transition reach.	Backwater induced from loch
	Water of Tullia	Scotland	13.9 / 0.6	0.4	0.0030 / 0.0004	Cfc	Upstream of the gravel-sand transition, the channel has a multichannel pattern with active lateral and medial bars. River becomes single-thread at the gravel-sand transition. Downstream fining is not smooth and does not transition to full sand bed conditions due to input of coarse sediment from river banks.	Backwater induced from loch (~1 km downstream)
	Beauty Creek	Canada	6.0 / 0.3	0.3	0.0040 / 0.00005	ET	Complex history and sediment supply as Beauty Creek is set within the larger Sunwapta braidplain.	Backwater induced from confluence with Sunwapta River
	Sunwapta	Canada	8.2 / 0.3	1	0.0045 / 0.0006	Dfc	Channel is ~500 m wide. Gravel section is braided, with actively migrating channels in loose glacial outwash sediment. As the sand content of the bed increases, the number of braid channels decreases and bars become more vegetated and stable.	Backwater induced from alluvial fan**
Frings (2011), Ylla Arbós et al. (2021)	Rhine	Netherlands	12 / 1.5	50	0.0002 / 0.00011	Cfb	Values are from the Waal River, a distributary channel of the Rhine conveying the majority of the flow. Sinuosity decreases from 1.38 to 1.12 across the transition. Channel geometry is controlled by human activity, mostly through channel narrowing.	Backwater induced (coastal)
Ichim and Rădoane (1990)	Siret	Romania	5.0 / 0.3	12	0.001 /0.0001	Csc	Coarse gravel material is delivered into the Siret from Carpathian tributaries. The GST occurs ~20km downstream of the Punta River confluence (the last Carpathian tributary).	Exhaustion of supply
Pickup (1984)	Ok Tedi-Fly	Papua New Guinea	31.0 / 0.2	10	0.01 / 0.001	AF	Not specified	Backwater induced (coastal)
	North Saskatchewan	**Canada**	**7.2 / 0.3**	**21**	**0.00019 / 0.00035**	**Dfb**	**Not specified**	**Exhaustion of supply****

Shaw and Kellerhals (1982)	South Saskatchewan	Canada	7.9 / 0.2	25	0.001 /0.001 No break in slope	Dfb	The transition occurs immediately downstream of the confluence with the Red Deer River which is sand-bed.	Exhaustion of supply/overwhelmed by sand**
	Peace	Canada	7.0 / 0.4	88	0.000074 / 0.000074 No Break in slope	Dfb	Not specified	Exhaustion of supply/overwhelmed by sand
	Athabasca	Canada	18.1 / 0.38	26	0.0012 / 0.00029	Dfc ET	Not specified	Exhaustion of supply/overwhelmed by sand
	Red Deer	Canada	37.4 / 0.3	25	0.00035 / 0.00030	Bsk	The gravel-sand transition occurs in the badlands which contribute a significant amount of clay, silt, and fine - medium sand into the channel.	Exhaustion of supply/overwhelmed by sand**
Dingle et al. (2016)	Kosi	Nepal	63 / sand	9	0.0013 / 0.0006	Cwa	Not specified	Exhaustion of supply - subsidence driven accommodation
	Gandak	India	18 / sand	15	0.0008 / 0.0002	Cwa	Not specified	Exhaustion of supply - subsidence driven accommodation
	Sharda	India	47 / sand.	40	0.0007 / 0.0004	Cwa	Not specified	Exhaustion of supply - subsidence driven accommodation
	Ganga	India	38 / sand	26	0.0012 / 0.00084	Cwa	Not specified	Exhaustion of supply - subsidence driven accommodation
	Yamuna	**India**	**34 / sand**	**32**	**0.0012 / 0.00066**	**Cwa**	Not specified	Exhaustion of supply - subsidence driven accommodation
Quick et al. (2019), Dingle et al. (2020)	Karnali	Nepal	50/0.3	~5-10	0.002/0.0005	Cwa	Transitions from braided/anabranching, multi-thread gravel bed channel to more sinuous, highly mobile sand bed channel. Alluvial bars in the sand channel are unvegetated and reworked each monsoon season. Low clay content in banks of the sand channel.	Exhaustion of supply - subsidence driven accommodation
Singer (2010)	Sacramento	USA	46 / 0.4	125	0.0075 / 0.001	Csa	Channel width decreases through transition and into sand reach. Increase in bed curvature through the diffuse transition that	Modified by anthropogenic inputs of sediment**

							extends over 100 km. Numerous anthropogenic disturbances over last 60 years that have mostly reduced gravel supply, but not sand supply.	
Knighton (1999)	**Ringarooma**	**NE Tasmania**	**35-40 / 1-2**	**6**	**Not specified**	**Cfb**	**No clear change in planform. Major input of mining waste (sediment size < 5 mm) from 1875 to 1984. As upstream supplies of mining waste became depleted, the gravel-sand transition migrated downstream. ~20 km reach where patches of gravel still persist on a largely sand bed.**	**Modified by anthropogenic inputs of mining waste****
Dubille and Lavé (2015)	Churre	Nepal	20 / 0.2	7.4	0.013/0.0007	Cwa	Transition occurs ~10-20 km downstream of the mountain front. Gravel portion is wide (200-400 m) and braided on the apex of a low-gradient alluvial fan. Channel progressively becomes more sinuous, narrower (50-100 m) and single-thread downstream of the transition.	Exhaustion of supply - subsidence driven accommodation
	Lakhandei	Nepal	9.8 / 0.5	10	0.005/0.001	Cwa	Gradual reduction in channel width across the transition (from 500 to 300 m) and a more abrupt narrowing ~15 km downstream to 50-100 m.	Exhaustion of supply - subsidence driven accommodation
	Bakeya	Nepal	11.9 / 0.03	12.6	0.005/0.001	Cwa	Gradual reduction in width across the gravel-sand transition from ~600 to 300 m over ~50 km.	Exhaustion of supply - subsidence driven accommodation
	Ratu	Nepal	22.2 / 0.2	8.4	0.008/0.001	Cwa	Gradual reduction in width from ~400-700 m in gravel reach to ~50-150 m in sand reach.	Exhaustion of supply - subsidence driven accommodation
Venditti and Church (2014) Venditti et al. (2015, 2019)	**Fraser**	**Canada**	**16.1/ 0.428**	**54**	**0.0005/0.00006**	**Cfb/Csb**	**Exits a series of bedrock canyons as a wandering gravel channel. Patches of gravel exist within a diffuse extension of the gravel-sand transition for ~9 km. Downstream of the diffuse extension, it adopts a sand bedded single-thread planform and is not actively migrating. The river then enters its delta where it bifurcates. Various anthropogenic controls on the river through these three reaches including rip-rap, dikes, scour protection.**	**Exhaustion of supply**
Dong et al. (2016)	Selenga	Russia	10-35/ silt and clay	~35	Not specified	Dwb	River bifurcates into 7 distributary channels before entering a lake. The	Exhaustion of supply - subsidence driven accommodation

							transition occurs upstream of the backwater limit. No clear change in planform across the transition.	
Not previously published	Pilcomayo	Bolivia	39.3/0.18	14	0.002/0.0007	Cwa	Channel exits a series of bedrock canyons as a 0.5-1 km wide braided gravel bed channel. The sand channel is wider (1-2 km), has less vegetated in-channel deposits and higher rates of lateral channel migration.	Exhaustion of supply - limited supply due to upstream abrasion in canyon system
Labbe et al. (2011)	Tualatin	USA	12.15 / 1.57	0.46	0.0023 / 0.0016	Csb	The transition corresponds with a decrease in channel sinuosity (1.7 in the gravel reach to 1.33 in the sand reach) and an increase in bank cohesivity from the gravel to sand reach.	Possible exhaustion of supply
Gomez et al. (2001)	Waipaoa River	New Zealand	7.9§ / Sand	< 2	Not specified	Cfb	Transition 2.5 km downstream of tidal limit. Instead coincides with change in neotectonics, from region of uplift to subsidence.	Exhaustion of supply - subsidence driven accommodation
Ferguson et al. (2011)	Vedder Canal	Canada	7.1 / 1.4	1.5	Not specified	Cfb/Csb	A low-gradient artificial channel diverting the Vedder River. Water discharge is unregulated. The canal is uniform straight and has stable vegetated channel banks. The canal has no tributaries or distributaries. In the upstream reach, the bed is predominately gravel with a near unimodal distribution.	Combination: seasonal backwater effect from the Fraser River. Also an exhaustion of supply at the distal end of an alluvial fan.
Harries et al. (2018)	Iglesia basin Alluvial fan 2	Argentina	13 / <2	Not specified	Not specified	BWk	Not specified	Exhaustion of supply – possibly lateral dispersion across fan
	Iglesia basin Alluvial fan 3	Argentina	19 / <2	Not specified	Not specified	BWk	Not specified	Exhaustion of supply – possibly lateral dispersion across fan

*Climate zone key (Beck et al., 2018): (BWk) Arid – Desert – Cold, (Cfa) Temperate – Without dry season – Hot summer, (Cfc) Temperate – Without dry season – Cold summer, (Cfb) Temperate – Without dry season – Warm summer, (ET) Polar – Tundra, (Dfb) Cold – Without dry season – Warm summer, (Dfc) Cold – Without dry season – Cold summer, (Csc) Temperate – Dry summer – Cold summer, (AF) Tropical – Rainforest, (Bsk) Arid – Steppe – Cold, (Cwa) Temperate – Dry winter – Hot summer, (Csa) Temperate – Dry summer – Hot summer, (Csb) Temperate – Dry summer – Warm summer, (Dwb) Cold – Dry winter – Warm summer

** Cause of transition stated in paper

§ An average grain size was calculated based on the 5 surface grain size measurements immediately upstream of the transition (over ~6 km distance).

While a change in channel planform may be expected across gravel-sand transitions, it is clear there are external factors that may complicate this signal (e.g., anthropogenic or glacial modification). Studies of individual gravel-sand transitions have identified changes in braiding intensity, sinuosity, and channel width (Sambrook-Smith and Ferguson, 1995; Frings, 2011; Dubille and Lavé, 2015). For example, Labbe et al. (2011) suggested that increased fine sediment and cohesivity in the bank material led to a narrower and deeper sand-bed channel across the gravel-sand transition in the Upper Tualatin River.

To test for changes in planform across a wider range of systems, we examined five rivers of various sizes in different climate zones (Table 1) using Google Earth imagery. We first determined a characteristic channel width for each river by taking channel belt width measurements across the gravel-sand transition, over a distance of 2 to 30 km, depending on the relative size of the river. For consistency, this characteristic channel width was used as a spacing interval for subsequent measurements of active channel width, braiding intensity and sinuosity over larger distances. We took fifty active channel width measurements upstream and downstream of the gravel-sand transition (Figure 4a), but excluded densely vegetated bars that are unlikely to be submerged during bankfull discharges. We normalized these measurements using the average width for clearer comparison between systems. Channel sinuosity was calculated for a total of 10 reaches on each river system, where each reach represents a downstream distance equal to 10 channel belt widths (Figure 4b). Sinuosity was defined as the ratio of the channel length, following the main channel path, to the straight-line distance between the beginning and end of the defined reach. We calculated braiding intensity for each of these reaches following Egozi and Ashmore (2008) using the channel count index method (Howard et al., 1970) (Figure 4c). Channels separated by bars with no vegetation cover were excluded from the channel count index to remove the influence of river stage.

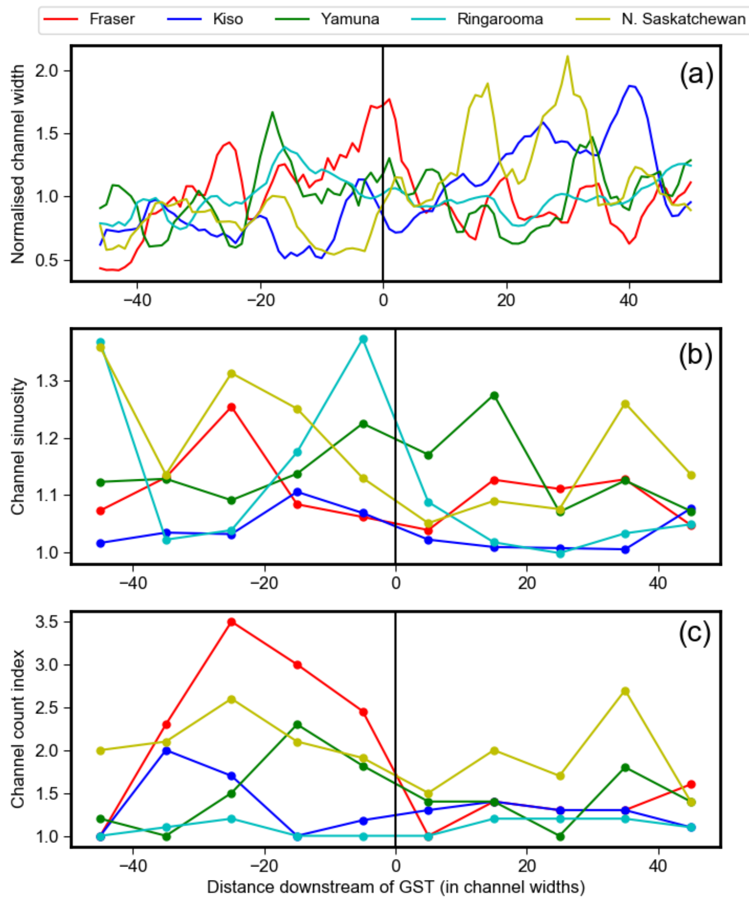

Figure 4. Downstream changes in (a) normalized active channel width, (b) channel sinuosity, and (c) channel count index across gravel-sand transitions in five river systems (see Table 1). Normalized channel width values in (a) are presented as a 5-point running average. All distances are relative to the position of the gravel-sand transition (GST) such that negative values are

upstream and positive values are downstream. Distances are measured in channel widths, based on the average channel belt width across the gravel-sand transition.

In contrast to Labbe et al. (2011), width of the North Saskatchewan and Kiso channels generally increases across the gravel-sand transition (Figure 4a). The maximum channel width of the North Saskatchewan River occurs 15 to 35 channel widths downstream of the gravel-sand transition after which it narrows (Figure 4a). Shaw and Kellerhals (1982) noted the potential influence of isostatic rebound on the downstream sections of the North Saskatchewan River, a result of an extensive ice cover during the last glaciation. Shaw and Kellerhals (1982) also suggested that progressive upstream migration of the gravel-sand transition in response to a rise in base level has placed the transition in a zone with a narrower channel width, associated with post-glacial incision. The Kiso River increases from half to over twice the average channel width over a distance of 50 channel widths (Figure 4a). Anthropogenic influences may drive this increase where the river flows through an urban area and is extensively diked. There is also a notable backwater caused by a dam ~17 km downstream of the transition.

Several rivers show a decrease in channel sinuosity across the gravel-sand transition (Figure 4b), although this is not a clear universal trend. A change in channel sinuosity (1.38 to 1.12) occurs across the gravel-sand transition on the Rhine River (Frings, 2011; Table 1). The greatest change in sinuosity occurs on the Ringarooma, decreasing from 1.37 in the reach immediately upstream of the gravel-sand transition to ~1 (i.e., the channel is straight). Changes in channel count between the gravel and sand reaches are also variable, although a clear reduction is evident on the Fraser River (Figure 4c). This is consistent with the change in planform expected across the gravel-sand transition, from a multi-channel gravel bed river to a single thread sand bed channel. The Ringarooma shows no change in braiding intensity across the gravel-sand transition. This may relate to large inputs of mining waste sediment sized < 5 mm, between 1875 and 1984, which has led to successive phases of aggradation and degradation (Knighton, 1999), prohibiting vegetation from developing on bar surfaces. Because these bars are typically unvegetated, they are not included in the channel count.

Our findings suggest that there are relatively few common morphological changes observed across documented gravel-sand transitions. While an abrupt reduction in channel gradient is observed in most, there are instances where the break in slope is more subdued. This may relate to sand supply, but also to the low vertical resolution of topographic data (e.g., from 90 m Shuttle Radar Topography Mission data) that may have been used to derive these slope values. Anthropogenic modification of many of the channels on which there are documented gravel-sand transitions also appears to influence potential morphological changes (e.g., channel width, length, braiding intensity) so it is unclear whether a universal signal truly exists.

2.4. Stability and migration of the gravel-sand transition

Over 10^2-10^4 year timescales, the position of the gravel-sand transition is expected to be relatively stable (e.g., Cui and Parker, 1998; Frings, 2011; Blom et al., 2017). Sediment-transport models have also been used to examine the effects of variations in sediment flux, subsidence rate, gravel fraction and diffusivity on alluvial basin stratigraphy and gravel front migration over longer timescales (e.g., Paola et al., 1992b; Robinson and Slingerland, 1998; Marr et al., 2000). The time-scale over which these variations occurred, relative to an equilibrium time set by the basin length and diffusivity (the latter determined by water discharge and stream type), controlled the migration rate and style (e.g. abrupt versus smooth) of the gravel-sand transition and its preservation in the sedimentary record (Paola et al., 1992b). The development of stable gravel-sand transitions and patterns of migration have also been considered in terms of patterns of subsidence, delta progradation and base-level rise in analytical modelling studies. Blom et al. (2017) used a model of sediment sorting to argue that downstream migration of the transition resulted from the necessity of a steep gravel wedge to transport the incoming gravel supply. As gravel was fed into the model, the length of the gravel wedge increased as gravel was deposited immediately downstream of the transition. Through time, the volume of gravel required to steepen the overall wedge also increased, resulting in a deceleration of the downstream gravel-sand transition migration. Increased rates of subsidence, sea level rise or delta progradation drive an upstream reatreat of the transition in aggrading environments. Even with a continuous gravel supply that should increase the volume of the gravel wedge, the position of the transition can remain stable due to the creation of accommodation in the gravel reach through subsidence, base-level rise and delta progradation (e.g., Paola et al., 1992b; Marr et al., 2000; Dong et al., 2016).

Documenting long-term migration rates estimates of the gravel-sand transition from surface deposits is complicated by seasonal changes in gravel mobility and sand cover (e.g., Venditti and Church, 2014), and transient responses to anthropogenic influences (e.g., Knighton, 1999; Singer, 2010; Ylla Arbos et al., 2021). In general, the gravel-sand transition should be stable over geomorphic timescales (Parker and Cui, 1998; Cui and Parker, 1998), in the absence of anthropogenic disturbances. Depositional records in alluvial basins may provide a longer-term picture of gravel-sand transition stability. Sedimentary cores from the Allt Dubhaig floodplain

(Scotland) suggested an 80 m retreat of the gravel-sand transition (due to the construction of a hydropower diversion dam) and subsequent 50 m readvance between ~1930 and 1997 (Sambrook-Smith & Ferguson, 1995; Blom et al., 2017). This would suggest that the gravel-sand transition migrated ~2 m/yr on average, based on a total migration of ~130 m over this period. Sedimentary cores from an unperturbed gravel-sand transition on the Fraser River (Canada) suggested limited migration of the transition over the past several thousand years (Roberts and Morningstar, 1989).

2.5 Gravel-sand transitions in the stratigraphic record

During periods of thrust wedge advancement and basin shortening, sediment deposited in alluvial basins downstream of convergent margins is incorporated back into the rock record, preserving information on changes in grain size associated with the gravel-sand transition. Abrupt changes in sediment grain size in vertical successions are typically interpreted as the result of tectonic or climatic forcing during the time of sediment deposition, such as a change in sediment flux or basin subsidence rate (e.g., Paola et al., 1992b; Robinson and Slingerland, 1998, Duller et al., 2010). A comparison between modern fluvial deposits in the proximal Himalayan foreland basin to deposits preserved in the frontal Siwalik belt (recycled foreland deposits exhumed by thin-skinned tectonic activity along the Himalayan mountain front) suggested that modern grain size patterns were analogous to the ancient deposits preserved in the Siwalik units (Dubille and Lavé, 2015). In both the modern river sediments and in particles preserved in ancient records, the ratio in median grain size across the gravel-sand transition was ~100. The sudden appearance of gravel in the upper units of the Siwalik series was suggested by Dubille and Lavé (2015) to correspond to crossing of the gravel-sand transition during steady migration of the gravel front, associated with a topographic load induced flexural wave, as opposed to changes in tectonic or climatic forcing.

3. Existing Theories

3.1 Size-selective transport forms gravel-sand transitions

Paola et al. (1992a) examined downstream fining using a long (45 m) flume with a poorly sorted bimodal sediment feed. The setup was large enough to allow for size selective downstream fining, while at the same time short enough to inhibit abrasion (Paola et al., 1992a). Sediment fed into the channel formed a downstream terminating gravel wedge. Above a threshold grain size in the medium sand range, grains were too large to be transported in suspension, and instead were transported as bed load to the end of the gravel wedge. These larger clasts could not be transported beyond the gravel wedge due to reduced shear stress downstream, imposed by the lower gradient sand bed reach. Instead, larger clasts deposited at the toe of the gravel wedge resulted in a gradual downstream migration of the gravel-sand transition. In contrast, smaller sand grains were transported beyond the end of the wedge, eventually deposited downstream, forming the sand bed (Paola et al., 1992a). The grain size change observed across the transition was more pronounced where the sediment feed bimodality was greater; suggesting the gravel-sand transition may arise because different grain sizes have different levels of mobility (Paola et al., 1992a; Seal et al., 1997). Subsequent work by Blom et al. (2017|) developed this idea to consider the position and migration of the gravel-sand transition in terms of the upstream gravel supply and how this drives spatial patterns of shear stress. To convey gravel through the gravel reach in their model, a relatively steep slope was required. As gravel was fed into the upstream reach, gravel deposition occurred immediately downstream of the toe of the gravel wedge, driving both a downstream migration of the transition and steepening of the gravel reach. This also forced the spatial transition in shear stress further downstream, allowing sand to be carried further in suspension. In both flume experiments (e.g., Paola et al., 1992) and modelling (e.g., Blom et al., 2017), the position of the transition is effectively controlled by the quantity and selective-deposition of the bimodal sediment mixture fed into the flume and model.

Transport of gravel and sand mixtures was further explored with bedload measurements and pebble tracing experiments from natural river systems, which demonstrated that strong downstream sediment fining might develop through size selective sorting during transport (Ferguson et al., 1996). As shear stress reduced downstream, the stress available to mobilize and transport larger particles declines. The preferential mobility of smaller particles increased with distance downstream, resulting in bed material load fining, relative to the bed surface. The deposition of finer bedload on the bed surface not only fined the bed surface at an enhanced rate, but also further reduced the availability of coarser material to be entrained. Eventually, sand grain sizes overwhelmed the bed surface.

Wilcock (1998) and Wilcock and Kenworthy (2002) used a series of flume experiments to propose that a small increase in the bed sand fraction (~30%) produced large decreases in the critical shear stresses required to mobilize gravel and sand. The decrease for sand sized particles was suggested to be larger than that of gravel, resulting in enhanced mobility of sand across the transition, accelerating hydraulic sorting at the transition and producing a discontinuity in sediment transport across these specific grain sizes. Under high discharges, gravel transport became locally enhanced due to a bed smoothing effect by the patches of sand, and reduction of available resting places on the bed surface, further enhancing the patchy nature of the mixed gravel and sand bed (Iseya and Ikeda, 1987; Ikeda and Iseya, 1988; Paola and Seal, 1995; Seal et al., 1997; Wilcock and Kenworth, 2002; Gran et al., 2006; Nelson et al., 2009). The development of a patchy gravel and sand bed has been suggested to modify sand transport rates (e.g., Gran et al., 2006), allowing for a transition between gravel and sand bed conditions to occur over a narrow range of surface sand contents. Flume experiments have demonstrated that when the sand fraction of the bed increases to >30-40%, a more continuous sand matrix with patches of surficial gravel develops (e.g., Wilcock, 1998; Wilcock and Kenworthy, 2002; Gran et al., 2006). This is consistent with field observations in the diffuse extension of gravel-sand transitions, where smaller patches of gravel persist along an otherwise sand bed (e.g., Venditti and Church, 2014; Ylla Arbos et al., 2021). In principle, the size-selective transport theory presents a means to generate the abrupt reduction in grain size associated with the gravel-sand transition, but requires a separate mechanism to explain the increase in bed sand content at the upstream end of the transition.

Subsequent modelling by Ferguson (2003) used these thresholds of incipient motion to examine the effects of size-selective transport on the development of gravel-sand transitions numerically. Using a bimodal (binary) grain size mixture (23 and 0.5 mm for gravel and sand, respectively), gravel and sand were supplied to the model domain at capacity rates and the entire sediment flux entering the model reach was deposited along the profile. Gravel deposited at the upstream end of the model domain, while sand deposited further downstream beyond the end of the gravel wedge (Ferguson, 2003). Median size of the binary grain size distribution fined in the downstream direction as the fraction of sand on the bed increased, due to an imposed concave channel profile and downstream reduction in shear stress. At the point in the downstream profile that shear stress fell below the threshold for gravel entrainment, the bed abruptly transitioned to sand, which is ensured by the binary grain size distribution of the sediment supply. There is no other possible outcome if the gravel stops moving; sand must make up the bed, forming a gravel-sand transition. What would have happened if other sizes existed in the model is not clear. Sediment sorting effects under these conditions are a function of the bimodality enforced on the system, meaning an abrupt reduction in grain size should occur over any sediment range chosen to be omitted (Parker, 1990).

Analytical models of gravel-sand transition migration celerity, enforcing a bimodal grain size distribution, have considered how the position of the transition responds to additions of gravel to an equilibrium sand bed reach immediately downstream (Blom et al., 2017). As the gravel reach lengthened, the volume of sediment required for aggradation increased and migration celerity reduced. Using gravel flux measurements from the Fraser River, migration celerity of the gravel-sand transition was modelled and compared to estimates of the position of the gravel front from Google Earth images (Blom et al., 2017). The model predicted up to ±100 m of migration of the gravel-sand transition from its initial position over a 50-year period, which was suggested to be comparable to observations on the channel over the same period. However, cover sands on the terminating gravel wedge in the Fraser River develop and disappear on decadal scales, giving the appearance of downstream migration of gravel bars (Venditti et al., 2015). The gravel-sand transition is marked by a shift from clast-supported gravel to matrix-supported sand. It is not possible to distinguish the migration of the clast-supported gravel deposits from cover sand migration in aerial imagery. The depositional architecture of the floodplain across the gravel-sand transition in the Fraser River valley suggests that the transition has remained in essentially the same position for thousands of years (Roberts and Morningstar, 1989).

3.2 Abrasion and abrasion-driven bimodality forms gravel-sand transitions

Observations in natural rivers and in flume experiments have demonstrated that abrasion cannot account for the rapid fining rates found across the gravel-sand transition (Paola et al., 1992a; Sambrook Smith and Ferguson, 1995; Ferguson et al., 1996). Yet abrasion may be an important factor in the development of bimodal grain size distributions which are a requisite of the size-selective transport theory, and a condition often associated with gravel-sand transitions. The earliest quantification of grain size change across gravel-sand transitions was in a series of rivers in central Japan (Yatsu, 1955). Median grain sizes of bed surface material reduced from ~20 mm to 0.5 mm across the gravel-sand transitions, over a downstream distance of a few kilometers (~6-12 channel widths). This rapid reduction in grain size was thought to relate to an inherent tendency for grain sizes of 2-4 mm to be preferentially crushed, which was later examined by Kodama (1994). Rotating drum abrasion experiments of andesite and chert pebbles suggested that there may be a tendency for larger clasts to preferentially crush smaller particles in grain size mixtures (Kodama, 1994), although the particle velocities in these experiments were considerably higher than natural systems. Subsequent work on a number of rivers in Alberta (Canada) documented the same abrupt reduction in grain size, which was attributed to an absence of sediment within the 1-2 mm diameter range (Shaw and Kellerhals, 1982).

More recently, Jerolmack and Brzinski (2010) argued that viscous damping of grain collisions sets a lower limit on gravel grain size of ~10 mm. They argued that below a Stokes number (*St*) of 10^5, abrasion rates tended towards zero due to reduced kinetic energy transfer during grain collisions, and the sorting of these bimodal sediments results in the development of gravel-sand transitions. However, subsequent experimental work on bedrock incision by abrasion of impacting particles revealed that particles between 1 and 10 mm do still collide, even when accounting for viscous dampening at St < 75 (Scheingross et al., 2014). Viscous dampening appeared to reduce bedrock erosion rates for low-energy impacts, rather than fully inhibit erosion. The proportion of viscously damped impacts only exceeds 35% at grain sizes <1.2 mm. At grain sizes >2 mm, fewer than 8% of grain impacts were found to be viscously damped (Scheingross et al., 2014).

Additional complications with attributing abrasion to the development of a bimodal grain size distribution specific to gravel and sand grain sizes is that the dominant grain size or by-product produced by coarse grain abrasion may not necessarily be sand. Controlled laboratory experiments have demonstrated that clay, silt, sand and gravel grain sizes can be produced by particle collisions and the specific grain size produced may be linked to properties or factors such as lithology and particle velocity (Kodama, 1994; Attal and Lavé, 2009). If gravel-sand transitions occur as a result of size-selective sorting of bimodal distributions formed by rapid abrasion or particle collision dynamics relating to fine gravel and sand, one would expect sediment within the grain size gap to be absent in other sedimentary environments, such as shallow marine environments and beach settings, where abrasion mechanisms are similar to those found in rivers (Lamb and Venditti, 2016). Yet, beaches and energetic shallow marine environments do have unimodal distributions composed of 1-10 mm sediment (McLean, 1970; Jennings and Shulmeister, 2002), showing that these sizes are not preferentially abraded in shear flows. Other studies examining caddisfly (Trichoptera) larvae in lowland rivers have highlighted that sediment used in larvae case-building is commonly within the sand to ~11 mm range, with certain species specifically utilizing 0.5-4 mm particles (Mason et al., 2019), again suggesting that these grain sizes are present in river systems.

Arguments for the importance of abrasion in generating bimodal grain size distributions in other parts of the river system are more physically sound. Miller et al. (2014b) considered changes in grain shape, mass and diameter through a fluvial network. Rather than focusing on specific grain sizes, they examined how the dominant processes controlling grain evolution evolved from abrasion in the catchment headwaters, to size-selective sorting in the lower gradient alluvial channel. Abrasion was suggested to be a two-phase process, where initial changes in grain diameter were minimal as abrasion acted to round sharp edges of blocky hillslope material (e.g., Domokos et al., 2014). While reducing grain volume and generating significant quantities of sand and silt, changes in grain diameter were more subtle. As the initial block evolved towards a more elliptical shape, changes in grain diameter became more apparent while the grain volume continued to reduce. Essentially, a reduction in grain volume occurs once the block is delivered into the fluvial network and is subjected to abrasive processes, but it is only detectable in grain diameter once an elliptical grain shape is achieved further down the fluvial network (Miller et al., 2014b). While it does not provide a physically-based explanation as to why minimum gravel grain sizes are found at ~10 mm, it does propose a mechanism for non-uniform abrasion rates across different parts of the fluvial network, which may preferentially or more quickly appear to abrade finer and more elliptical gravel particles. More direct observations are needed regarding how fluid effects may relate to non-uniform abrasion rates that could be specific to these grain sizes.

Shaw and Kellerhals (1982) also considered the idea of preferential abrasion of 1-4 mm particles, although this idea has never been tested. These grain sizes were hypothesized to be the smallest grain sizes in the gravel bed and therefore more frequently transported and subjected to crushing and abrasion. The finer products of this process should then be entrained into suspension. It seems more likely however, that these grain sizes would simply raft downstream and become buried in the sand bed (e.g. in dune troughs), such as was observed in the diffuse extension of the Fraser River (Venditti and Church, 2014; Venditti et al., 2015) and in the Vedder Canal (Ferguson et al., 2011).

Over sufficiently long transport distances and in the absence of lateral inputs of sediment, lithology dependent abrasion may result in the development of bimodal grain size distributions. The lithology of coarse sediment exported from the Himalayan mountains is dominated (>50%) by quartzite, despite quartzite only representing ~10% of the mountainous catchment lithology (Dingle et al., 2017). These mechanically strong particles fine downstream at very low rates, resulting in a coarse quartz-rich gravel population, and a finer sand mode dominated by the byproducts of abrasion of non-quartzitic Himalayan lithologies.

3.3 Washload deposition

More recently, the emergence of gravel-sand transitions has been explained as a result of suspension deposition from washload. The sediment load of an alluvial river can be classified as being bed material load or washload. Church (2006) defines bed material load as transport of sediment that makes up the lower bed and banks of a river and is chiefly responsible for setting the channel morphology. The bed material load may be transported as bedload (traction or saltation) or as intermittently suspended sediment. Church (2006) defines washload as the transport of material that once entrained in a reach, is not redeposited. This occurs because washload sized material has advection lengths that greatly exceed the length of the reach (Venditti et al., 2015). Washload material is well represented in the upper banks and floodplain of a river (Church, 2006), but does not generally contribute to setting the channel slope or width (Paola et al., 2001). Washload particles are continuously exchanged with the bed, but never deposit (e.g., Lamb et al.,

2020) so they are poorly represented in the bed surface and lower bank grain size distributions. These particles may also be present in interstitial spaces in coarser bed material, having been trapped by interstitial flow or having infiltrated the gravel bed, but they play no role in setting channel morphology (Hill, et al. 2017). These definitions of bed material load and washload relate to the process through which sediment is transported; it is not tied to specific grain sizes. Within a given reach, grain sizes that were transported as washload under one flow regime, may be transported as bed material load under a different regime.

Venditti and Church (2014) observed that sand carried as washload in the gravel reach of the Fraser River, British Columbia (Canada) at high flows begins to deposit at the gravel-sand transition due to a distinct break in water surface slope at the termination of the gravel reach. In the lower gradient sand bed reach, sand is carried as intermittently suspended bed material load. Subsequent observations of shear stress at various flows by Venditti et al. (2015) showed that the median bed material size cannot be carried as washload in the sand bed reach. Furthermore, sediment advection lengths at the upstream end of the gravel-sand transition indicated that medium sand could not be carried in suspension for more than one channel width, suggesting that sand must be rapidly deposited. This idea requires a break in water surface slope that causes lower shear stresses in the sand bed reach and higher stresses in the gravel bed reach.

Lamb and Venditti (2016) proposed that gravel-sand transition may emerge from washload deposition, but a pre-existing water surface slope break is not necessary. They argued that the gravel-sand transition and the grain size gap can emerge due to the nature of suspension thresholds. Niño et al (2003) showed experimentally that the transition to suspension becomes increasing difficult at small particle Reynolds Number (Re_p) defined as:

$$Re_p = \frac{\sqrt{RgD}D}{v}$$

where *D* is the particle diameter, *v* is the kinematic viscosity of the fluid, *g* is acceleration of gravity and *R* is the submerged specific density of sediment. At $Re_p < 27$ there is a viscous effect on resuspension of particles being exchanged between the bed and the overlying fluid. This inhibits the vertical exchange of particles necessary to maintain washload. Lamb and Venditti (2016) developed a model combining the thresholds for bedload motion and washload suspension. The model suggested that at formative bed shear velocities (u_f^*) of ~0.1 ms^{-1}, there is a dramatic decline in competence to entrain sand into washload that coincides with the threshold to deposit the gravel fractions in a mixture. Formative bed shear velocity is defined as the shear velocity associated with formative discharge or flows (i.e., bankfull) where the D_{90} grain size is at the threshold for entrainment (Lamb and Venditti, 2016). At greater flows, the largest grains on the bed are entrained and the channel morphology is adjusted to accommodate the larger flow (Wolman and Miller, 1960). There is a narrow range of formative shear velocities over which the sizes in the grain size gap range can exist on the bed. They showed that beds composed of 1 to 5 mm grains are unlikely to exist because an increase in u_f^* will suspend the finer fractions into washload creating a gravel bed, and a decrease in u_f^* will cause rapid deposition of sand.

The washload theory does not require an absence of material within the grain size gap, but instead predicts that gap material exists but is simply never the dominant bed material size. The theory also provides physical rationale for why sand is rapidly deposited downstream of a gravel wedge. The theory does not require a pre-existing break in slope to generate a gravel-sand transition, but does require that the river reach a point where the $u_f^* = 0.1$ ms^{-1} threshold is crossed.

The reason that threshold is crossed could be from an exhaustion of gravel (e.g., Dong et al., 2016; Dingle et al., 2017) or an imposed backwater (e.g., Sambrook-Smith and Ferguson, 1995), both of which generate a reduction in bed slope and u_f^*.

3.4 Synthesis of theories

Size selective transport and abrasion processes generate downstream fining in rivers. There is no physically-based evidence that abrasion is capable of making an abrupt transition. However, abrasion does generate bimodal grain size distributions, which are commonly observed upstream of gravel-sand transitions. Reasons as to why that bimodality is focused around a grain size gap of ~1-5 mm are not clear, and there is no robust mechanism that demonstrates that abrasion generates a gap that is specific to those grain sizes.

The role of downstream fining in the development of gravel-sand transitions is more complicated. To produce gravel-sand transitions in existing size-selective transport models, gravel and sand are treated as two separate fractions and modelled separately. Those that consider a full grain size distribution omit sediment within the grain size gap range to force an abrupt gravel-sand transition. Size selective transport may act to amplify the abruptness of the reduction in grain size across gravel-sand transitions where a bimodal grain size distribution already exists, but it does not provide an explanation as to why the gravel-sand transition and grain size gap occurs across such a specific range of grain sizes.

The size selective transport theory does not need to consider the dynamics of washload (e.g., Blom et al, 2017). However, the washload deposition theory does not contravene the size selective transport theory. It provides an explanation for why sand is rapidly deposited when gravel transport ceases at formative discharges. The washload deposition and size selective transport theories suggest physical mechanisms through which gravel-sand transitions develop. It is possible that the role of abrasion and size selective transport in creating bimodal grain size distributions, and the role of size selective transport or washload deposition in creating abrupt gravel-sand transitions could vary depending on location. The dominance of these processes in any given setting may contribute to the observed variability in gravel-sand transition characteristics (e.g., length, change in gradient). To further examine the apparent lack of universal signal in gravel-sand transition morphological characteristics that we have identified, we utilize existing field data of documented gravel-sand transitions. By exploring whether commonalities across their characteristics and geographical settings exist, further insights as to whether any particular theory appears more consistent may emerge.

4. Controls on the location of gravel-sand transitions

There appears to be a relatively clear pattern of gravel-sand transition spatial distribution. They tend to occur either a small distance from mountain fronts, or in backwater zones (Figure 1). A number of gravel-sand transitions are found relatively small distances downstream of mountain ranges in alluvial plains or basins, where channels become laterally unconstrained and channel gradients are reduced. Gravel-sand transitions also commonly appear to occur when gravel is transported into a hydraulic backwater, with the transition occurring near where flow is first affected by downstream base level. Both conditions produce a break in the water surface slope that imposes a rapid reduction in transport capacity that could lead to the development of a gravel-sand transition.

4.1 Exhaustion of gravel downstream of mountain ranges

In many instances, gravel bed rivers persist downstream of mountain ranges for only a few (<10) kilometers (Dingle et al., 2017). The distance gravel can remain in transport depends on the characteristics and quantity supplied into the alluvial system, as well as the transport capacity of the system. Closely coupled channels and hillslopes within mountain ranges ensure a steady supply of coarse material into channels that are typically steep and laterally constrained. Much of this material will be transported downstream. On exiting the mountain range, the gradient of the downstream landscape is rapidly reduced and channels become laterally unconfined, promoting the deposition of the coarse fractions of the sediment load, while finer grain sizes continue to be transported (e.g., size-selective transport). This is consistent with the experimental observations of Paola et al. (1992) and modelling by Blom et al. (2017). Coarse sediment can be accommodated either vertically by subsidence (e.g., Paola et al., 1992b) or laterally, where channels avulse over the surface of largely unconfined low gradient alluvial fans (e.g., Reitz et al., 2010). The rate of downstream fining in alluvial systems is typically determined by factors such as the distribution and magnitude of basin subsidence and the input grain size distribution and supply (e.g., Paola et al., 1992b; Robinson and Slingerland, 1998; Marr et al., 2000; Duller et al., 2010; Whittaker et al., 2011; Dingle et al., 2017). In the absence of lateral inputs, all coarse sediment exported from the mountains will eventually be deposited upstream of a gravel-sand transition, or discharged into the ocean in coastal ranges where the gravel reach extends to the coast.

Across the Himalayan foreland basin, the gravel-sand transition is found within ~10-40 km downstream of the mountain front in most rivers. This distance is independent of upstream catchment area, discharge and sediment supply, and instead correlated to gravel flux and patterns of basin subsidence (Dingle et al., 2016; 2017). The gravel flux is also independent of catchment area, and instead appears limited by selective abrasion of weaker rock lithologies during transport within the mountain range. Only gravel sourced within ~100 km upstream of the mountain front survives downstream into the foreland basin, placing an upper limit on the amount of gravel exported out of the Himalaya (Dingle et al., 2017). Downstream of the mountains, sand is carried largely in suspension over a gravel framework-supported bed with a small (<15%) sand content (Dingle et al., 2016). Over a distance of a few kilometers, there is an abrupt gravel-sand transition downstream of which an exclusively sand bed channel exists.

We have made similar observations downstream of the southern Bolivian Andes, where rivers draining east into the alluvial Chaco Plain (Table 1) have limited gravel after they exit the mountain range (Pilcomayo River), or even transition directly from a bedrock canyon to a sand bedded channel (Parapetí River). The Parapetí River drains largely recycled sedimentary lithologies that characterized the sub-Andean fold-thrust belt (Horton and DeCelles, 2001), which are quickly abraded from gravel to sand on passing through the final bedrock canyon reaches and exiting the mountain front. The larger Pilcomayo River drains a more lithologically diverse catchment containing mechanically stronger lithologies producing gravel (and coarser particles) that do not abrade down into sand as quickly, maintaining a gravel bed channel further downstream into the Chaco Plain.

Gravel-sand transitions identified in several distributary channels of the Selenga River Delta (Russia) were found upstream of the upper limit of backwater influence, and more than 1500 km downstream of the main gravel source of the system (Dong et al., 2016). Given the continuous feed of gravel into the Selenga River, Dong et al. (2016) concluded that gravel must be removed during transport within the delta; otherwise it would be expected to prograde into the receiving basin. The gravel was thought to be buried below the active topset, a result of earthquake driven subsidence. The volume of subsidence driven accommodation produced by these earthquakes, occurring approximately every 300 to 500 years, exceeded the gravel supply from the upstream catchment between earthquakes, effectively fixing the position of the gravel-sand transition (Dong et al., 2016).

These observations from the Himalayan foreland basin and Selenga delta are complemented by numerical modelling examining the effects of base level change (subsidence) and abrasion on the stabilization of gravel-sand transitions (Cui and Parker, 1998). The key mechanisms found to arrest the position of the transition by Cui and Parker (1998) were when the sand transport reached capacity and overwhelmed the gravel (often subduing the break in slope commonly associated with the transition) when the gravel ran out. The exhaustion of gravel in the model was caused by a reduction in gravel transport rate in response to subsidence driven bed aggradation, and the abrasion of gravel into sand (Parker and Cui, 1998).

The distance downstream of mountain ranges (or gravel source areas) that the gravel-sand transition develops appears to be a function of gravel supply, water discharge and the distribution of subsidence generated accommodation (e.g., Paola et al., 1992b; Robinson and Slingerland, 1998). For example, where rates of subsidence are lower, gravel beds may be expected to persist further downstream (for a given gravel supply) when compared to systems with higher rates of subsidence and greater vertical accommodation close to the mountain front (e.g., Dingle et al., 2017). The reduction in gravel supply downstream of mountain ranges occurs through declining lateral inputs of coarse material, as channels and hillslopes become increasingly decoupled, and in some instances through abrasion of weaker lithologies. Where rivers discharge into subsiding alluvial basins, the coarsest fraction of the load is extracted and infills subsidence generated accommodation where sediment transport rates are reduced; sediment may also be laterally reworked across the surfaces of unconfined alluvial fans. Tributaries continuing to deliver coarser gravel grain sizes may extend gravel bed conditions further downstream within the main channel, until these lateral inputs also disappear, or the system is overwhelmed by sand. The creation of both vertical and lateral space in which to deposit sediment, combined with a reduction of lateral inputs in regions downstream of mountain ranges results in the rapid deposition of the coarsest sediment fraction and a break in channel bed slope. In instances where gravel supply and subsidence rate remain relatively constant in time, the position of the gravel-sand transition would be expected to be stable in space (e.g., Paola et al., 1992b).

The exhaustion of gravel supply from mountain ranges induces a break in channel gradient (Figure 5). Gravel bed rivers necessarily have steeper slopes to transport the supplied gravel load (e.g., Blom et al., 2017). Sand bed rivers have a lesser gradient (e.g., Parker et al., 2007), which leads to a break in the water surface slope (and therefore shear stress) where the transition occurs. This exhaustion of gravel supply comes from 1) a finite quantity of coarse sediment being exported from the mountains, and 2) the creation of vertical and lateral accommodation (e.g., change in lateral confinement, subsidence) which traps coarse sediment close to the mountain front in a lower gradient alluvial environment, with reduced transport capacity.

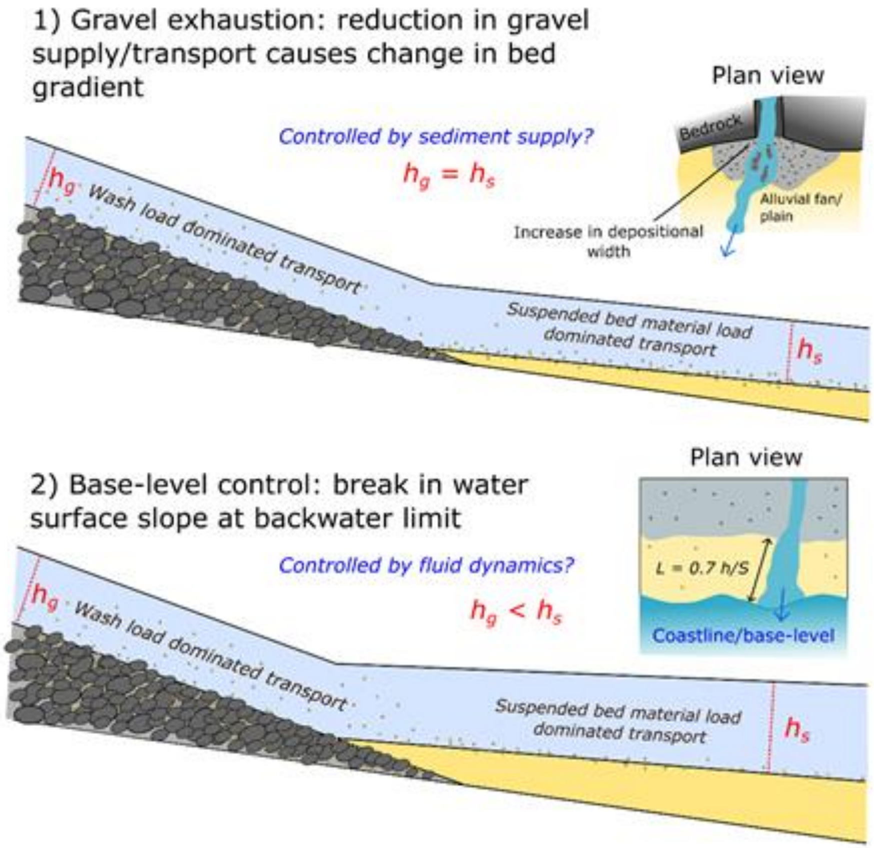

Figure 5. Schematic of changes in channel gradient, flow depth, planform and sediment transport regime across gravel-sand transitions formed by 1) gravel exhaustion (i.e. downstream of mountain ranges) and by 2) base-level controls (i.e. backwater induced).

4.2 Backwater or base-level controlled

A number of abrupt gravel-sand transitions coincide with a backwater generated above a local base-level control, where a rapid decline in the transport capacity of the river exists (Pickup, 1984; Sambrook-Smith and Ferguson, 1995). Abrupt gravel-sand transitions within a number of small Scottish rivers were within ~500 m upstream of standing bodies of water and alluvial/debris fans.

An alluvial fan extending across the Sunwapta River valley (Alberta, Canada) induced a ~1.7 km backwater reach where the position of the gravel-sand transition was thought to correspond with the backwater limit (Sambrook-Smith and Ferguson, 1995). Here, we define the backwater limit as the upstream limit of where river flow is influenced by downstream effects (e.g., Chatanantavet et al., 2012; Kimmerle & Bhattacharya, 2018). The length over which these effects occur can be defined as normal flow depth (i.e., the flow depth upstream of the limit) divided by average bed slope (e.g., Ganti et al., 2016). The position of this limit may not be spatially fixed through time.

Studies looking at the location of avulsion nodes in low-gradient channels on delta lobes have also suggested that sediment deposition occurs in zones of spatial flow deceleration under low flow conditions (Chatanantavet et al., 2012; Ganti et al., 2016). This non-uniform flow exists due to the disequilibrium between the normal flow depth upstream of the backwater limit, and the river depth at the shoreline (Ganti et al., 2016). If the reach immediately upstream of the backwater limit is gravel bed and the coarsest material in suspension is sand sized, then it seems logical that flow deceleration would force sand out of suspension in the upper reach of the backwater, initiating a gravel-sand transition. While a backwater effect can result in a rapid decline in transport capacity that may promote the development of a gravel-sand transition, not all backwaters will produce gravel-sand transitions. Both gravel and sand grain sizes need to be present within the system at the backwater limit. The degree of bimodality within the gravel and sand modes within grain size distribution may also determine the abruptness of the transition.

There may also be competing effects between the gravel supply and backwater mechanisms. For example, in the Fraser River, British Columbia, the gravel-sand transition occurs at the termination of a gravel wedge ~60 km downstream of the mountain range (Venditti and

Church, 2014). At low flows the backwater limit from the ocean is just a few kilometers downstream of the transition. During high flows when most sediment transport is occurring, the backwater effect is negligible, suggesting it is not the dominant control.

The observation that gravel is exhausted near the point where backwater effects begin to occur may not be coincidental. Downstream of the transition, lower sand reach gradients allow the backwater effect to extend upstream. If the backwater reach extends up to a steeper gravel reach, the backwater cannot penetrate much further upstream because the gravel reach is necessarily steeper to transport gravel. In this sense, the backwater limit forms where gravel is exhausted from the system. If the gravel front starts to advance, there may also be competing effects between the channel bed and the water surface which may drive the backwater limit downstream. In these instances, the cause and effect of the position of the backwater limit and gravel-sand transition is less clear.

4.3 Synthesis

By comparing documented gravel-sand transitions globally, we have identified common patterns in their location. Gravel-sand transitions appear to occur primarily close to backwater limits or downstream of mountainous regions (Figure 5). Gravel supply downstream of mountain ranges decreases as the coarsest fraction of the sediment load is deposited. Deposition is promoted through the generation of vertical (e.g., subsidence, consolidation of sediments) and lateral (e.g. avulsing or migrating channels where channels become laterally unconfined) accommodation across these surfaces (Figure 5). Our observations are also consistent with modelling (e.g., Paola et al., 1992b, Blom et al., 2017) that shows changes in base level and gravel supply drive migration of the transition. We also find that morphological characteristics (e.g., changes in channel width, sinuosity and slope across the transition) are variable between individual rivers, and likely depend on location or system specific factors (e.g., sand supply, anthropogenic influences).

By comparing our global observations with our review of existing gravel-sand transition theories, it is apparent that there are distinct factors controlling different aspects of the gravel-sand transition. First, the location of the transition appears to be largely controlled by a balance of gravel supply and accommodation (i.e., a mass balance effect), or backwater hydrodynamics. In some cases the backwater may be coincident with the point where gravel is exhausted in a system because backwater effects cannot penetrate very far upstream in steep gravel bed reaches. Secondly, the nature or characteristics of the transition (i.e., its abrupt reduction in grain size, framework structure, apparent grain size gap) can be explained by granular effects such as size-selective transport or washload deposition. The exact nature of these granular effects is more difficult to determine and is considered in more detail below.

5. Discussion

Of the proposed theories concerning the abrupt nature of the gravel-sand transition, only two specifically address changes in sediment transport across the gravel-sand transition (size-selective transport and the washload deposition theories). Using new observations collated from the global database (Table 1), we consider how these observations relate to each theory.

5.1. Size-selective transport and bimodal grain size distributions

To generate an abrupt gravel-sand transition through size-selective transport of particles, two conditions are necessary. First, a downstream reduction in shear stress is required. This can be achieved through a concave downstream profile that results in a progressive decrease in capacity to transport the coarsest fraction of the sediment supply. Second, a bimodal grain size distribution is required, with modes in the sand and gravel fractions (>5 mm). The size-selective transport theory also requires the absence of particles within the grain size gap range. The reasons for the grain size gap are not immediately obvious, so it is useful to consider its origin.

5.2. Origin of the grain size gap

Bimodal grain size distributions are commonly found in gravel bed rivers, although different river systems display different ranges of gap grain sizes. Sizes that are generally depleted in most gravel bed rivers are between 1 and 5 mm (Figure 1). A grain size gap could occur due to sampling bias. Bed surface grain size measurements (e.g., point counts and photo-sieving) often focus on larger particles present, meaning particles in the grain size gap range may be underrepresented (e.g., Wolman, 1954; Ibbeken & Schleyer, 1986 ; Rice and Church, 1998; Bunte and Abt, 2001; Pearson et al., 2017; Purinton and Bookhagen, 2019). Volumetric or bulk sampling of subsurface material is not subjected to the same operator bias, although some loss of finer material to the deeper subsurface may occur. Similarly, where full grain size distributions are not presented, it is not possible to discern whether a median D_{50} statistic (which is commonly reported in isolation) demonstrates the presence or absence of material within the grain size gap range. Nevertheless, careful sampling of bed material has shown that the grain size gap is a real feature of bed material in gravel bed rivers (e.g., Shaw and Kellerhalls, 1982, Wolcott, 1984; McLean, 1990; Ham, 2005; Rice and Church, 2010).

Potential reasons for the grain size gap in river bed sediments are that the material is: 1) preferentially abraded in transport (e.g., Shaw and Kellerhals, 1982), 2) not supplied from the hillslopes (e.g., Wolcott, 1988), 3) depleted in gravel reaches due to superior mobility of fine gravel (Ikeda, 1984; Wilcock et al., 2001, Venditti et al., 2010a) or 4) that grain size gap material is present in the tails of both the bed and washload grain size distributions, but never the dominant mode in either (Lamb and Venditti, 2016).

5.2.1 Preferential abrasion and abrasion-driven bimodality

It has been suggested that bimodal grain size distributions are caused by preferential abrasion once delivered to the channel, such that grain sizes within the gap range are gradually removed with increasing distance from their source (i.e., there are grain size dependent abrasion rates). As noted already, there is currently no evidence to support the idea that grain size dependent abrasion rates specifically focused around the 1-5 mm fraction exist. Viscous damping of particle collisions at grain sizes of ~10 mm (Jerolmack & Brizinski, 2010) should also generate a bimodal grain size population, setting a lower limit of gravel grain sizes at this threshold. However, gravel grain sizes finer than 10 mm are present in many environments and experiments have shown that this process should not become important in particle collisions until grain sizes are < 2 mm (cf. Scheingross et al., 2014).

5.2.2 Hillslope supply

Material within the grain size gap could naturally be largely absent from fluvial systems because it is simply not produced on hillslopes. Studies directly comparing hillslope sediment size production to channel bed grain size are limited and there are inconsistencies in results. In some instances, there are close resemblances between hillslope and channel grain size distributions (Wolcott, 1984; Wolcott, 1988), while in others the relation is less clear (Ibbeken, 1983). Grain size analysis on a number of rivers draining the east Carpathian mountains (Rădoane et al., 2008) suggested the degree of observed bimodality at the gravel-sand transition was driven by the mixing of distinct grain size distributions from different sources. Sand sized inputs were produced by hillslope erosion of friable lithologies within the drainage basins, which were thought to overwhelm the gravel supply.

Sklar et al. (2017 & 2020) recently examined patterns in down valley hillslope grain size. Grain size measurements from hillslope surface material in Inyo Creek (Sierra Nevada) revealed increasingly finer grain sizes with increasing distance down valley, with many distributions being bimodal (Sklar et al., 2020). At middle and lower elevations, the dominant mode and median grain sizes were typically within the 1-10 mm range, suggesting that sizes associated with the grain size gap were supplied to the channel. Comparable measurements from the active channel bed were not presented, so it is unclear how grain size gap material in the hillslope distributions translates directly to bed surface distributions. In contrast, landslide sediment and soil grain size distributions on hillslopes contributing sediment to the Feather River (Sierra Nevada) were found to be generally devoid of large quantities of material within the grain size gap (Attal et al., 2015). Median grain sizes of sediment extracted from soil pits were typically less than 1 mm, while landslide sediment median grain sizes were 50-100 mm (70% of the landslide deposits were coarser than 10 mm).

While it appears that there are parts of the landscape where the grain size gap material is not being produced in large quantities, there are others where it is. This may relate to location specific conditions (e.g., lithology, climate, gradient) that favor the generation of specific grain size distributions and sizes. The observation that material within the grain size gap range appears to be produced within the hillslope weathering engine, but rarely forms a dominant mode within river bed surfaces, suggests two possibilities. First, these hillslope grain sizes may not translate directly to channel bed surface distributions. Many of these studies focusing on hillslope grain size distributions are in relatively steep upland landscapes, and considerably upstream from where a gravel-sand transition might be expected to occur. Second, the relative importance of sorting processes may increase as channels become increasingly decoupled from hillslopes.

5.2.3 Superior mobility.

Experimental work has shown that that addition of fine sediment to an otherwise immobile gravel bed is capable of enhancing the mobility of the gravel bed (Jackson and Beschta, 1984; Iseya and Ikeda, 1987; Ikeda and Iseya, 1988; Wilcock and McArdell, 1993, 1997; Wilcock, 1998; Wilcock et al., 2001; Wilcock and Kenworthy, 2002; Curran and Wilcock, 2005; Venditti et al, 2010a; 2010b). Venditti et al. (2010a) showed that finer material effectively smoothed the bed surface by filling interstitial pockets. This resulted in fluid acceleration in the near-bed region, due to reduced turbulence at the sediment boundary, and mobilized particles that had been immobile prior to the introduction of the finer sediment pulse (Venditti et al., 2010a). Later experimental work showed that the addition of finer grains to a coarser bed may also cause a bridging effect, dependent on the ratio of coarse to fine grain sizes, closing gaps in the surface layer of the coarser bed framework (Dudill et al., 2017, 2020) which may enhance gravel transport. It is possible that this effect could deplete a gravel bed of grain size gap material that would naturally fit into the interstices of the coarser gravel framework, allowing those sizes to raft over the gravel bed and disperse into sand beds downstream (e.g., Ikeda and Iseya, 1988; Wilcock et al., 2001), where it is then likely buried. These grain sizes are therefore never well represented in gravel surface grain size distributions. Field observations from the Waipaoa River in New Zealand by Gomez et al. (2001) showed a sub-surface D_{50} in the range of ~2 to 7 mm over a distance of ~90 km with a bed surface D_{50} between ~7 to 20 mm (Gomez et al., 2001). This suggests that the bed surface of the Waipaoa River may have been depleted in gap material that had been present in the system. While median statistics should be treated with caution in the absence of full grain size distributions, the large supply of fine gully material formed by sheared and crushed fine grained sedimentary rocks (D_{50} ~ 6 mm) suggests that grain size gap material was being fed into the river channel (Gomez et al., 2001).

5.2.4 Transport mode separation.

The grain size gap may also result from the different ways gravel and sand are transported in gravel bed rivers. Sand is necessarily transported as washload in gravel bed rivers at formative flows, interacting with the bed, but never forming persistent deposits at flows large enough to transport gravel as bed load. This has been demonstrated in observations of sand and gravel transport in the Fraser River British Columbia. Mclean et al. (1999) showed that at flows just above the mean annual flow (<5000 $m^3 s^{-1}$) bedload in the gravel bed reach was mainly sand, but as discharge exceeded 5000 $m^3 s^{-1}$, the bedload was composed of gravel bed material and sand was carried in suspension. The formative flow is the mean annual peak flow (~9000 $m^3 s^{-1}$) during which sand is carried as washload. This observation was confirmed by hydraulic calculation of bedload and suspension thresholds by Venditti and Church (2014). Lamb and Venditti (2014) used a broader compilation of data to show that when the coarsest particles on a gravel bed are entrained into bedload, the sand mode is carried as washload. This showed that sand deposits in gravel bed rivers on the waning limb of hydrographs as cover sands, but is then entrained as flow rises and at peak flows, it is carried as washload.

Lamb and Venditti (2016) have shown that the shear stress at which 10 mm gravel begins to distrain from bedload corresponds to the stress at which sand transitions from washload to suspended bed material load. At u_f^* values of ~0.1 ms^{-1}, the washload deposition theory predicts that material within the grain size gap should fall within the tail end of bed material size distribution in the gravel bed (fine tail) and sand bed (coarse tail) reaches, and so never forms the dominant mode in either reach. As a result, these grain sizes are poorly represented by median statistics (D_{50}) in either the gravel or sand reaches. Combined with the superior mobility of gap material and bridging effect (Dudill et al., 2017, 2020), this transport mode separation could deplete the bed surface of gap material as sand is being deposited, leaving two bed grain size modes, as discussed below.

5.3. The washload deposition theory and gravel supply

Unlike the size-selective transport theory, the washload deposition theory predicts that a gravel-sand transition should be able to form without a bimodal grain size distribution. If such as distribution were present, the physics described by the washload deposition theory may also simply enhance any existing bimodality.

The washload deposition theory predicts that a gravel-sand transition could emerge on a smooth concave longitudinal profile, however an abrupt reduction in bed slope could also force u_f^* values to fall below the threshold required to suspend fine particles as washload. An abrupt reduction in bed slope could occur through an exhaustion of gravel supply downstream of mountain ranges, or through externally forced gravel deposition in backwater regions (Figure 5). Both mechanisms will generate a reduction in u_f^*, as the characteristic gradient necessary to transport material in a gravel bed channel is greater than that of a sand bed river. As gravel supply reduces, u_f^* values similarly reduce eventually crossing the u_f^* = 0.1 m/s threshold and sand should start to deposit on the bed initiating an abrupt gravel-sand transition. The only requirement of the washload deposition theory is a u_f^* value of ~0.1 ms^{-1}. There are no assumptions about sediment bimodality, which makes the explanation universal, unlike the size-selective sorting theory. Importantly, the washload theory does not preclude other processes (e.g. size-selective sorting or abrasion) or conditions (bimodality) from enhancing the sharpness of the gravel-sand transition.

5.4. Key remaining questions

While the size-selective transport and washload deposition theories provide physically-based explanations for how gravel-sand transitions develop, further validation of both theories is required. The size-selective transport theory requires grain size distributions to be bimodal. Grain sizes within the grain size gap range appear to be present on hillslopes, but not in channels. Our understanding of what happens to these grain sizes, once delivered to the fluvial network, remains unclear. The physics of these grain sizes needs to be better constrained in order to implement them into morphodynamic models to explore how the transition responds to changes in discharge, base-level, sediment supply and caliber (e.g., Blom et al., 2017). The washload deposition theory predicts that an abrupt gravel-sand transition should develop even with a unimodal grain size distribution. Evidence from direct field observations or physical experiments of how these grain sizes are distributed between the bed surface and suspended load is needed to test this. Further understanding of suspension thresholds for different grain sizes is needed (e.g., Niño et al. 2003; de Leeuw et al., 2020; Lamb et al., 2020) as these thresholds underlie the washload deposition theory. A better understanding of how the deposition of washload onto the channel bed influences fine gravel mobility is needed. Finally, while our analysis of morphological characteristics of gravel-sand transitions suggests there are limited commonalities (grain size, slope), many of these metrics are derived from low spatial resolution data sets (e.g., 90 m digital elevation models). Detailed studies over a greater range and scale of river systems would help predict the types of changes that would be expected in natural channels, and how best to manage these types of river systems where abrupt changes in channel morphology may present a change in river-related hazard (e.g., Dingle et al., 2020).

6. Conclusions

Gravel-sand transitions occur in all gravel bed rivers where the river loses the capacity to carry gravel. Their distribution is global yet we still lack a universal solution to explain their development. The main theories for gravel-sand transition formation are abrasion, size selective transport and washload deposition. Only the size selective transport and washload deposition theories provide a physical mechanism through which gravel-sand transitions may develop. The size selective transport theory requires a downstream change in shear stress and a bimodal size distribution to form a gravel-sand transition. Both are commonly observed in gravel bed rivers. The washload deposition theory does not require a bimodal grain size distribution, but does require a decline in shear stress. The washload theory also explains why there is a relative absence of river beds dominated by the grain size gap material.

Through a global analysis of gravel-sand transitions, we have shown that gravel-sand transitions appear to occur either a small distance downstream of mountain ranges or a characteristic backwater length upstream of a local base-level control or coastline. Downstream of mountain ranges, gravel is rapidly extracted from the sediment supply to infill subsidence generated accommodation. The relatively steeper slope required to transport gravel through the gravel reach ensures that sand is carried in suspension beyond the gravel front. Flow deceleration associated with a backwater region may promote gravel deposition, but it is less clear how the stable position of the transition relates to the backwater limit, where gravel progradation may cause the backwater limit to migrate. Both gravel-exhaustion and flow deceleration associated with backwater effects provide the conditions necessary for mechanisms associated with the size-selective transport and washload deposition theories to initiate. Our review brings new perspectives on controls of the position and characteristics of the gravel-sand transition. We suggest that allogenic factors such as gravel supply and subsidence rate determine the location or position of the gravel-sand transition. We attribute the abrupt spatial extent and grain size reduction associated with the transition to autogenic processes (i.e., size-selective sorting and washload deposition). There are still outstanding gaps in our understanding of how hillslope sediment supply transfers to river bed surface grain sizes, and how sediment within the gravel-sand transition grain size gap is transported and deposited once delivered into fluvial networks. Research into these areas should be a priority.

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