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Journal of Geophysical Research (Earth Surface): Commentary

Stuck at the bar: larger-than-average grain lag deposits and the spectrum of particle mobility

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Abstract

Larger-than-average grain deposits in gravel-bed rivers potentially exert a distinctive influence upon fluvial morphodynamics and flow resistance. They are products of historical contingency; sourced from rare events that supply atypically coarse material. Larger-than-average grain lag deposits are emblematic attributes of the Tongariro River, New Zealand. They are deposited on bar edges and heads. Derived from lahar valley floor deposits that subsequently became terraces, these materials are less likely to be reworked across a range of flows compared to other bar material. Conceptual models that consider channel configuration and incorporate distributions of particle mobility and flood flows are necessary to assess the role of larger-than-average grain deposits on river morphodynamics.

Key points

1. Larger-than-average grain deposits are products of historical contingency
2. Larger-than-average grains exert an important influence upon the evolutionary trajectory of some gravel bed rivers
3. Predictive morphodynamic models require feedbacks between channel configuration and distributions of both particle mobility and flood flows

Key words

Gravel-bed river, legacy sediment, sensitivity, sediment transport, grain size distribution, flood flow distribution.

Larger-than-average grains matter

Larger-than-average particles moderate rates of incision in bedrock rivers, thereby influence the evolution of longitudinal profiles (e.g., Hanks and Webb, 2006). Alongside their impact upon flow resistance (Monsalve et al., 2017; Recking, 2009), larger-than-average sediment grains also exert a distinctive control upon the morphological adjustment of rivers (MacKenzie et al., 2018). This observation has primarily been motivated by laboratory experiments (Mackenzie and Eaton, 2017) that investigated channel pattern evolution, channel mobility and active width using grain size distributions (GSD) that were characterised by similar median (D_{50}) GSD but slightly different coarse tail GSD. These experiments showed that sediment mixtures with larger D_{84} grain size resulted in channels that were characterised by less morphological reworking and lateral erosion. These findings challenge the notion that a characteristic grain size (e.g. D_{50}) and a single flow magnitude (e.g. bankfull; 2.33 year flood) can adequately represent feedbacks between flow, sediment and morphology. Instead, insight into fluvial morphodynamics and thus evolutionary trajectories (Brierley and Fryirs, 2016) of river systems requires consideration of distributions of bed material and flood events (Church and Ferguson, 2015), and their relations to channel configuration. The results from laboratory experiments also prompt the need for an examination of field data to appraise the presence, sources, distribution and role of large grain deposits in contemporary riverscapes. In this commentary, we underpin the experimental recognition of the role of large grains with a field perspective, illustrated by observations of the imprint of larger-than-average grain lag deposits along the Tongariro River in Aotearoa, New Zealand. We also consider the implications for investigating fluvial morphodynamics and associated management strategies.

Sources of larger-than-average grains in nature

The GSD of bars and channel beds in gravel-bed rivers is related to: existing in-situ sediment; the supply of sediment from the catchment upstream and erosion of upstream bars, floodplains, terraces and fans; the susceptibility of the deposited sediment to reworking by high flow events of differing magnitude and frequency; and feedbacks between vegetation growth and removal (Church, 2006; Gurnell, 2014; Reid et al., 2019). The entrainment, transport and deposition of grains that are larger than median is commonplace. For example, experiments have shown that coarse particles or bed load sheets can stall as they exit zones of high shear stress, resulting in the formation of medial or lateral bars (Lisle et al., 1991; Ashmore, 1993), and observations in natural mobile rivers have also shown that particles 3-4D_{50} can be transported considerable distances (e.g. Church and Hassan, 1992). However, less attention has been given to particles that are even coarser (>6-8D_{50}; Figure 1) which are outside the realm of normal fluvial transport.

Larger-than-average grain deposits commonly reflect legacy sediments, thereby providing a record of past sedimentological and rare hydraulic events (e.g. James, 2013). As such, they exemplify how historical contingency (e.g. Beven, 2015; Brierley, 2010; Buffington, 2012; Davidson and Eaton, 2018; Brierley and Fryirs, 2016; Phillips, 2011) may exert an important influence on contemporary fluvial morphodynamics. We term these deposits *lag* since their effects are likely to persist through time. These deposits, which represent end members on a distribution of bed mobility, are typically characterised by a distinct source, thereby warranting classification as lag deposits (Figure 1). Such deposits are evident in both transport- and supply-limited conditions (Montgomery and Buffington, 1997). For example, Church and Slaymaker (1989) show how lag deposits may be associated with historic glacial, fluvial or paraglacial processes in supply-limited post-glacial landscapes. As greater energy is required to rework sediments than is available in the contemporary setting, large grains are stranded in channels or on outburst plains (e.g. Evans, 1991). In transport-limited bankfull conditions with abundant sediment supply, large grains supplied to the channel are likely to either remain in-situ due to selective transport (Brummer and Montgomery, 2006) or be deposited immediately downstream of a sediment source on gravel bar heads. Larger-than-average grains are only likely to become mobile during the largest floods when channel pattern becomes unstable (Eaton and Church, 2004). In recently volcanically influenced settings, lag deposits typically arise from sediment that has been transported during lahars (Cronin et al., 1997). Lag deposits may also be generated as a result of anthropogenic legacy effects (James, 2013), including placer mining (James et al., 2009) and the construction and subsequent removal of temporary dams to create outburst floods to float timber downstream (Napier et al., 2009; Polvi et al., 2014). These activities mobilise finer grains and leave erosional scars and remnant large grain deposits. Rivers in urban areas can also retain a legacy of unnatural larger sediment such as concrete from construction, bricks or aggregate from roads (Gregory et al., 2008).

Case study: Tongariro River and lag deposits

The influence of past geological events upon contemporary fluvial morphodynamics is emblematic for many New Zealand rivers which are subjected to various forms of perturbation associated with tectonic, climatic and anthropogenic impacts. In response, large grains line valley floors as a result of volcanic, glacial, paraglacial, fluvial and anthropogenic processes. This is exemplified by the 47 km long Tongariro River which drains the Volcanic Plateau of the Central North Island. Headwater areas include the active andesitic volcanic cones of Mounts Ruapehu (2797 m), Tongariro (1981 m) and Ngauruhoe (2287 m). The river flows into Lake Taupo, a rhyolitic caldera formed by a catastrophic eruption 1800 years ago (Wilson and Walker, 1985). This eruption reset a lower base-level for the river, causing it to incise into the tephra and lahar deposits delivered from the upstream volcanic cones. We speculate that the buoyant pumice and finer sand material were rapidly flushed, leaving a lag of larger boulders which had been delivered by events which transported larger material than is generally moved by the contemporary river regime. These lag deposits influence the morphodynamics of this gravel-bed river. The Tongariro remains a conduit for lahar material, with earliest deposits dated back to 14.7 ka (Cronin et al., 1997) and most recently from the Mt Ruapehu eruption between 1995 to 1996, which delivered 6900 kilotonnes, two-thirds of which was comprised of fine grained sediment (Collier, 2002; Manville et al., 1996). As a result, the bed of the river channel contains a boulder lag which acts as an armour layer, slowing the rate of adjustment, especially vertically, within the system.

Figure 1 shows the distribution and size of larger-than-average grain lag deposits on four bars on the Tongariro River. These bars represent changes in overall grain size along the lower course of the Tongariro, downstream from a dam (see Reid and Brierley, 2015). The calibre of the thirty largest clasts is considerably greater than the sediment that makes up the majority of the bar surface (b_{max}/D_{50} range is 6-11). Larger-than-average grain lag deposits are predominantly located at bar heads and along the upstream river-edge. These findings in a natural setting corroborate recent experimental observations about deposition locations in aggradational settings (Booker and Eaton, 2019). Bar head clustering is far more distinct for Bain Bar compared with the other three upstream bars. Bain Bar is located downstream of terrace confined reaches, within a transport-limited setting. Once mobilised by large floods, particles are likely to have been transported considerable distances to be located at this bar. Two-dimensional flow modelling to calculate gravel-bar reworking for this bar indicated particles at the bar head, where the lag is deposited, were unlikely to be entrained during a 100 year flood (Reid et al., 2019). The other three bars are in supply-limited, terrace confined settings. Model predictions show a distribution of mobility for larger-than-average grains: units of Blue Bar with lag deposits are mobile during 50-100 year floods; the bar edge units with lag deposits at Red Hut Bar are largely immobile in a 100 year flood; and units with lag deposits at Breakfast Bar are mobile during 20-100 year floods. These results indicate that consideration of grain size distribution, channel configuration, reach setting and flood flow distribution are necessary to evaluate the stability of larger-than-average grain lag deposits on bars.

Larger-than-average particles may influence patterns and rates of channel adjustment. This can be conceptualized as the geomorphic sensitivity of channels (Reid and Brierley, 2015; Fryirs, 2017). The presence of lags at bar heads causes wake-shadow effects, providing persistent flow separation and subsequent downstream bar stability. As large floods are required to rework this coarse material (Reid et al., 2019), channel adjustment only occurs during larger flows in terrace-constrained reaches. For example, flood events with a c.20 year recurrence interval are required to remove vegetation and rework some parts of these bar surfaces, while downstream reaches near the delta experience more continuous rates of adjustment (Reid and Brierley, 2015). Overall, the lag acts as key stones that structure the contemporary bar morphology and sedimentology.

Implications for fluvial morphodynamics

Figure 2 presents a conceptual model of the geomorphic impacts of larger-than-average grains upon the morphodynamic evolution of the Tongariro River across various time and space scales. Given their persistence as fundamental sedimentological building blocks, larger-than-average grains influence flow hydraulics at smaller spatial scales through the steering of flow and influence on roughness through the effects of protrusion. This may impact upon channel geometry/planform (Eaton and Church, 2004; Eaton et al., 2010), thereby influencing the operation of sediment conveyor belts (Ferguson, 1981). Larger-than-average particles also influence physical habitat for living organisms (Jowett and Richardson, 1990; Quinn and Hickey, 1990). At the scale of individual particles, seminal work on equal mobility (Andrews, 1983; Parker and Klingeman, 1982) showed that the largest individual clasts in a gravel mixture were not entrained at the same threshold as all the other particle sizes. Thus, to analyse their influence on turbulence, particle entrainment and transport thresholds, larger-than-average particles should be considered in context of their particle cluster setting and relation to nearby particles (Brayshaw et al., 1983; MacKenzie and Eaton, 2017; Masteller and Finnegan, 2017; Papanicolaou and Tsakiris, 2017). Beyond the contemporary riverscape, it remains to be seen how the sedimentological signature of lag deposits is represented in the rock record, extending assertions of selective deposition from extreme events (Ager, 1973).

The identification of larger-than-average particle deposits draws into question the applicability of equilibrium or regime models in explaining contemporary channel form and morphodynamics. It also focuses attention on how alluvial rivers are defined (Eaton and Millar, 2017), leading to the unresolved question of “how much lag do you need to not have a fully alluvial river?” Historical contingency may exert an important influence upon how contemporary rivers work, through both sediment supply and the geomorphic responses to a given sequence of flood events (cf., Beven, 1981). In addition to laboratory experiments, numerical simulations also offer opportunities to explore how the supply and presence of large grains impact upon feedbacks between flow, sediment transport and form, thereby contributing to analyses of the influence of historic events upon contemporary sediment flux, geomorphic unit assemblages and the evolution of riverscapes. Contemporary models that incorporate multiple grain sizes and unsteady flow (e.g., Williams et al., 2016) can be used to investigate bed surface stability as proposed by MacKenzie et al. (2018).

Larger-than-average particle deposits may be located on a river’s bed, subaerially exposed on its bars or line bank toes. They may also be vertically or horizontally buried. As these materials may have a significant impact upon geomorphic adjustment in a particular river reach, it is important to examine both surface sediment and a river's below ground sedimentology. Maps of the former may be feasible using remote sensing to map spatially distributed grain size (e.g. Carbonneau et al., 2005; Pearson et al., 2017; Woodget and Austrumns, 2017) but the latter will continue to require traditional field analyses (cf., Hoyle et al., 2008). If a source of lag deposits is identified, then assessment of a river's connectivity to the source and the timescale for the legacy sediment to be exhausted is also required, as this may influence the rate of sediment conveyance through the system and the resulting sediment budget. For example, coarse lag materials may affect the sediment delivery ratio from a particular reach (Fryirs et al., 2007). As they influence the geomorphic sensitivity of a river (Fryirs, 2017; Reid and Brierley, 2015), thresholds of particle mobility induced by lag materials may influence the evolutionary trajectory of a river, thereby presenting key insights to support river rehabilitation planning and design (Cluer and Thorne, 2014).

Conclusion

Larger-than-average grain deposits arise from a variety of origins. Their influence upon the morphodynamics of gravel-bed rivers is an open question. Although laboratory experiments have demonstrated the capacity for large grains to dampen morphological adjustment, few studies have identified the imprint of larger-than-average grain deposits upon evolutionary trajectories in field situations. Investigation of the role of larger-than-average grain deposits on fluvial morphodynamics, whether through fieldwork, laboratory experiments or numerical modelling applications requires conceptual models that incorporate insights into: (i) particle mobility distribution; (ii) flood flow distribution; and (iii) channel configuration. Together, this more complete treatment of interactions between sediment, flow and morphodynamics will enable the quantification of the role of larger-than-average grains and the feedbacks they induce.

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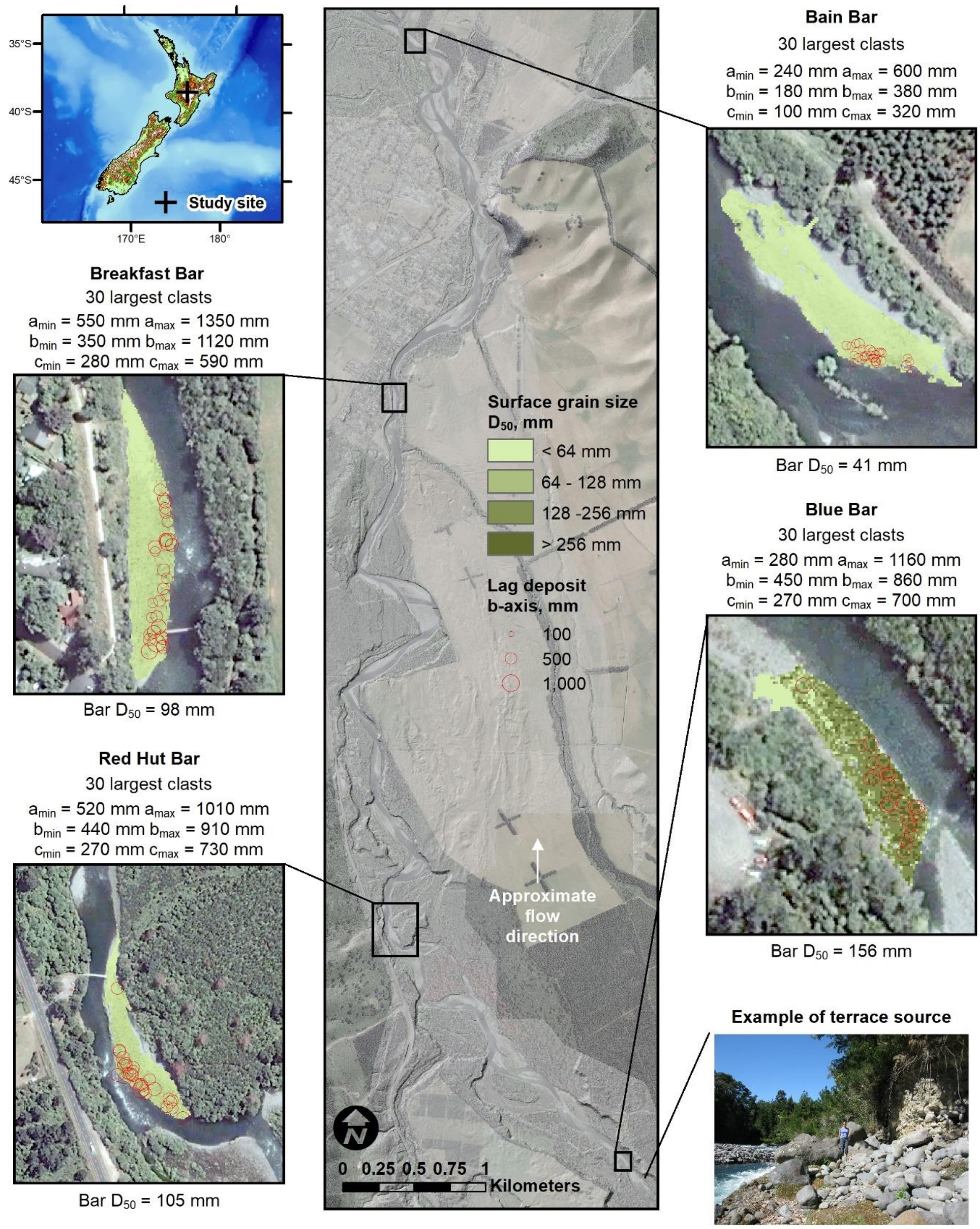

Figure 1 Distribution and size of the 30 largest grains on four river bars on the Tongariro River, New Zealand. Minimum and maximum grain size statistics are for the 30 largest grains. Spatially distributed grain size maps are based on a relationship between b-axis grain size and detrended standard deviation elevation from terrestrial laser scanning (Reid et al., 2019). The D_{50} grain size for each bar is the median grain size mapped from this relationship.

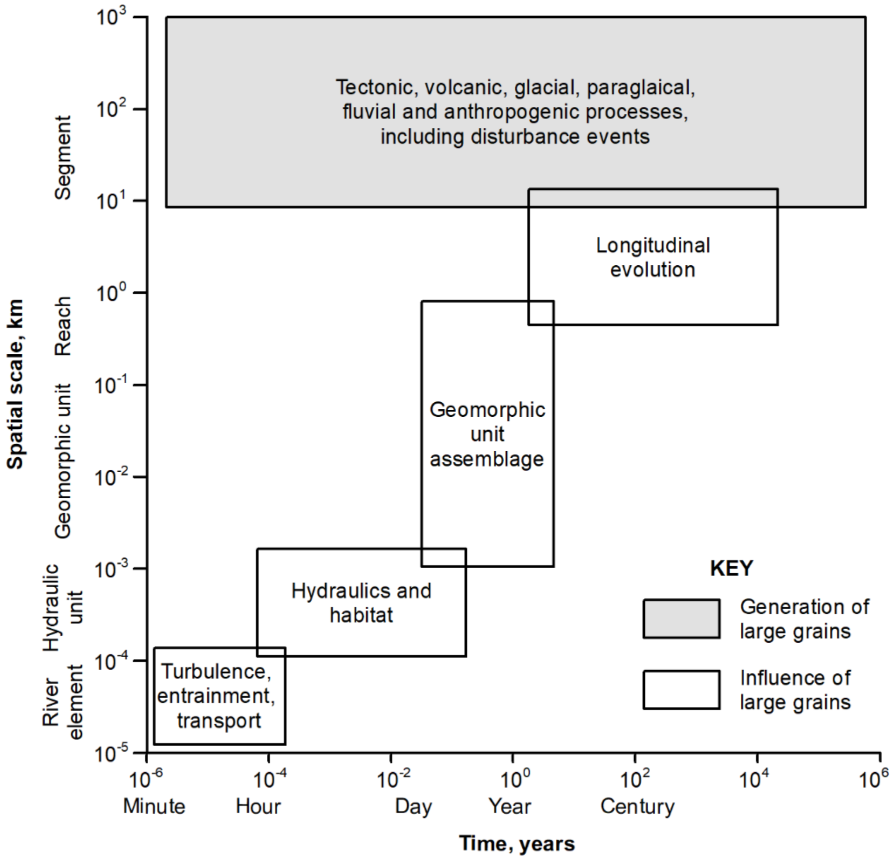

Figure 2 Conceptual model showing the time-space scales across which larger-than-average grain lag deposits are supplied to a river system and their subsequent influence upon fluvial morphodynamics. This conceptualization assumes that the lithological hardness of larger-than-average particles supports their preservation and persistence.

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