Estimates of Gravel Transport Rates in Mountain Streams for Normal ($Q_{1.5}$) High-Flow Events

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Abstract

This study takes an empirical approach to address the problem of predicting gravel transport rates in mountain streams. A total of 96 worldwide datasets on gravel transport relations versus water discharge were compiled including the writers' measurements and datasets from the literature. Unit rates of gravel transport occurring during a common high-flow event $q_{B,1.5}$ were computed for each dataset and plotted vs. a modified stream power parameter $\omega_{1.5}$. Most of the data pairs, $q_{B,1.5}$ vs. $\omega_{1.5}$, fell along the plot's central zone about two orders of magnitude wide. Within that zone, $q_{B,1.5}$ increased with $\omega_{1.5}$ following a power function. Data falling above or below the central zone were found to be associated with exceptionally high or low sediment supply, respectively. The plotted relations of $q_{B,1.5}$ vs. $\omega_{1.5}$, together with qualitative information of a site's watershed's and channel's situation of sediment supply, can then be used to obtain estimates of $q_{B,1.5}$ for unsampled streams. Estimates of $q_{B,1.5}$ also provide a context for evaluating measured or predicted transport rates relative to values for other streams.

1. Introduction

Knowledge of gravel transport rates in mountain streams is important for studies concerning fluvial research, channel restoration, watershed management and assessments of channel response to changes in water or sediment yield. Transport rates that occur during common high-flow events, such as the annually to biennially recurring flood are often of specific interest. However, reliable information on gravel transport is difficult to obtain in mountain streams.

Various studies (e.g., Gomez and Church, 1989; Johnejack and Megahan, 1991, Martin and Ham, 2005) have found that bedload transport equations—typically based on flume experiments—grossly mispredict bedload transport rates in gravel-bed streams through steep terrain. The equations are not designed for flow tumbling over rocks and steps, and they cannot account for large differences in bed mobility and sediment supply between streams. Computed transport rates are not only highly uncertain but also lack context; i.e., a user is offered no insight on whether a computed transport rate is high or low for a given stream with its specific characteristics. A study may conduct its own field measurements, but this approach is laborious and likely error-prone if expertise and suitable field equipment are not available.

To mitigate the prediction problem for gravel transport rates in mountain streams, this study takes an empirical approach and evaluates a large compilation of gravel transport relations (transport rates vs. discharge) measured in a variety of streams. Most measurements were made in mountain streams, and all measurements were taken with samplers suitable for gravel bedload. Based on the compiled transport relations, the study plotted transport rates predicted for commonly occurring high-flow events in relation to a modified stream-power parameter. In combination with a qualitative assessment of a channel's sediment supply, the resulting plots serve to estimate gravel transport rates for a common flood for a study stream. The plots also provide a reference that allows a user to compare gravel transport rates measured in a study stream to rates expected in other streams.
Several arguments speak for focusing the analyses on transport rates associated with a commonly occurring high-flow event such as the 1.5-year recurrence interval flow \((Q_{1.5})\). The ability to conduct field measurements and then to predict a certain transport rate from them was the main reason. Transport is often still measurable with physical samplers at flows near \(Q_{1.5}\), and a transport relation measured to only 50-70% of the \(Q_{1.5}\) flow can often be reasonably extrapolated to the \(Q_{1.5}\) flow. By contrast, bedload samples can usually not be collected in very large events such as the \(Q_{20}\). Besides, transport rates associated with a \(Q_{20}\) flow are highly variable between events because transport may be controlled by external sediment input (e.g., debris flows, bank collapse) or retention (e.g., in debris dams or overbank). Transport rates for the \(Q_{20}\) flow are therefore not inferable from a transport relation measured accurately to the \(Q_{1.5}\) flow.

The study selected the hydrologically defined \(Q_{1.5}\) flow as a basis for analyses because \(Q_{1.5}\) can often be computed with more certainty than the morphologically determined bankfull flow. While several writers noted close similarities between the \(Q_{1.5}\) flow and bankfull flow (Dury, 1976; Leopold, 1994; Castro and Jackson, 2001), the similarity holds only for streams with active gravel floodplains, but not for gravel-bed streams in which the cross-section is carved into largely immobile banks or is shaped by the largest flood events. It also does not hold when water or sediment supply have changed. Another complication is that a stream’s bankfull flow level may be determined morphological, graphical, or hydraulically, and resulting bankfull estimates may differ widely between methods and also between operators (Williams, 1978; Johnson and Heil, 1996; Radecki-Pavlik, 2002), which lead Williams (1978) to conclude that no firm ratio exists between the \(Q_{1.5}\) flow and bankfull flow. Owing to this lack of clarity, this study focuses on the hydrologically defined \(Q_{1.5}\) rather than morphologically, graphically, or hydraulically defined bankfull flow.

2. Methods

2.1 Data compilation

Data for this study are partially based on the gravel transport relations sampled by the writers in 12 high-elevation Rocky Mountain streams and one stream in the Eastern Cascades (Bunte and Swingle, 2019). Most of the writers’ bedload samples were collected with bedload traps (Bunte et al., 2004, 2007, 2008); a large-frame net sampler was used at one site (Bunte, 1996) and pit traps at another site (Bunte, 1997).

To extend the database numerically and geographically, the writers compiled a worldwide set of 70 gravel transport relations, predominantly from mountain streams, where bedload was measured with samplers suited for coarse beds: bedload traps, vortex samplers, pit-type samplers, unflared wide-mesh basket samplers, hanging baskets and large-frame net samplers. Bedload measurements made with a Helley-Smith sampler (or other pressure difference samplers such as the Elwha and the TR2 samplers) were not included in this study, because Helley-Smith measurements greatly over-predict actual rates when transport is low and under-predict them when particles are streaming into the sampler and exceed mid-sized gravel sizes (Bunte et al., 2019, this volume).

Geographically, the literature data represent streams in many mountain areas worldwide. Within Canada, data come from the interior of British Columbia (Harris Creek: Hassan & Church 2001; Church & Hassan 2005; Elk and Cotton Creek: Green et al. 2013, 2014a) and the Alberta Rocky Mountains (Bridge Creek: Nanson 74). Within the U.S., there are data from the Pacific North-West (Oak Creek: Milhous 1973; Flynn Creek: Estep and Beschta, 1985; Beschta 1981; N.F. Caspar Creek: Hassan et al., 2014); the Northern Rocky Mountains of WY and MT (East Fork River: Emmett, 1980; Leopold and Emmett, 1997; Dupuyer Creek: Whitaker and Potts 2007 a and b); the Great Basin (Hobble Creek: Hinton 2012) and the South-East (Goodwin Creek: Kuhnl, 1992; R. Kuhnl, pers. comm.; the Goodwin Creek tributaries WS13 and WS14: Kuhnl, 1991; 1992); and Little Turkey Creek: McMahon, 2013).

The European Alps are presented by data from Austria (the Pitzbach: Hofer 1987; Turowski & Rickenmann, 2009; the Rofenache: Habersack et al., 2015a; Gattermayr, 2013; the Urslauf: Kreisler et al., 2016; Fischbach and Ruetz: Rickenmann, 2018); from Switzerland (the Riedbach: Schmid 2011; Schneider et al. 2015b; the Erlenbach: Rickenmann et al., 2012); from Italy (Río Cordon: Lenzi et al., 1999, 2004, 2006; Saldur Bach: L. Mao, per. comm., Dell’Agnese et al., 2014); as well as in the Spanish Pyrenees (Tordera: Garcia et al., 1996, Laronne et al., 2001).
Steep mountain streams in other areas of the world include the New Zealand Alps (Torlesse Creek: Hayward, 1980; Hayward and Sutherland, 1974), the Chinese Yunnan Province in the southeastern Himalaya (Diaoga: Yu et al., 2009), the Chilean Andes (Estero Morales: L. Mao pers. comm.; Ravazzolo et al., 2019); southern Brazil (Arvoresinha: G. Merten, pers. comm.), the Karakorum (the Talo, Gosak, Gulshanabad, Duber, and Kandia streams: Palt, 2001); and central Japan (Yotagiri, Uchida et al., 2018; Hirakawa and Kamashigawa: Handa et al., 2013; Mitsunaga et al., 2015; Sakurai et al., 2016).

Besides mountain streams, the data include channels in Israel’s Negev desert (Nahal Yatir and Nahal Esthemoa: Reid et al., 1995, 1996; Powell et al., 1998; Laronne et al. 2003; Bergmann et al., 2007; Cohen et al., 2010; Alexandrov et al., 2007); as well as pool-riffle streams in northern Italy (Virginio Creek: Tacconi and Billi 1987; Cencetti et al., 1994); in Great Britain (Turkey Brook: Reid et al., 1985, 1986 a, b; Avon: Downs et al., 2016; Soar and Downs, 2017), and in Canada (Elbow River: Hollingshead, 1971).

The data include measurements from a few large-valley streams, draining catchments of 800 - 2200 km² in the Alps (the Isel and Drau: Habersack et al., 2015b, Habersack et al., 2016), the Elwha River in the Pacific NW (Hilldale et al., 2014; Magirl et al., 2015), and the Vedder River in British Columbia (McLean ’80; Martin and Church ‘95). The data compilation also includes large foreland streams draining 6,000 – 250,000 km²: (the Danube in Slovavia: Holubova et al., 1998, 2004; Camenen et al., 2011, Liedermann et al., 2012); the Rhine in Switzerland: Nesper, 1937; Meyer-Peter et al., 1937) and the Fraser River in Canada: McLean et al., 1999; Ferguson and Church, 2009).

2.2 Data analysis

2.2.1 Determining the Q₁.5 flow: In the writers’ study streams, the Q₁.5 flow was determined from long-term flow records or from scaling a flow record from a gauging station reasonably close to the study stream. Datasets from the literature were more likely to provide information on bankfull flow (and its channel dimensions) rather than referring to the Q₁.5 flow, and some publications use the term bankfull in the sense of “boardfull” (i.e., as flow overtopping the banks) in which case the reported bankfull flows may be significantly larger than Q₁.5. This study carefully evaluated whether reported bankfull flow values represented Q₁.5 and, if needed, estimated Q₁.5 by searching the publication for comments on the relative magnitude of the measured event or turning to other publications about the same stream. For some sites, information on Q₁.5 was found in hydrological publications, or Q₁.5 was estimated from a published multi-year hydrograph. Sometimes, a plotted cross-sectional profile together with an estimate of the stream’s active width from Google Earth images gave clues about the Q₁.5 level; and, in some cases, bankfull values or estimated Q₁.5 values were evaluated against plotted regional relations of Q₁.5 vs. basin area, A.

2.2.1 Establishing a gravel transport relation: A gravel transport relation was determined for each measured set of field data by fitting a power function in the form of

\[ Q_B = a \cdot Q^b \]  \hspace{1cm} (Eq. 1)

to measured gravel transport rates \(Q_B\) and instantaneous discharge \(Q\). The coefficient \(a\) and the exponent \(b\) were empirically determined and refer to \(Q_B\) in units of g/s and \(Q\) in m³/s. When several downstream locations were sampled at a study stream or when a site was resampled in a later year, two power functions were fitted to one stream’s data. Two power functions were also fitted when the transport relation displayed notable hysteresis following changes in intra-seasonal sediment supply. By contrast, literature data collected over multiple years were usually combined to one dataset, unless the study specifically pointed out inter-annual differences.

Transport relations measured by the writers in Rocky Mountain streams exhibited steep, straight trends in log-log space over the entire range of sampled flows, allowing standard curve-fitting (Eq.1) to be applied. Adjustments to a standard curve-fitting approach were required when a plotted dataset exhibited large scatter or data were scant, when the trend was curved in log-log scale, or when data were not presented in a log-log plotting scale. To avoid an overly flat relation that results when a power function is fitted to log-log plots with scattered data or only a short range of sampled flows, the data envelope was used as a guide to fit a trend line by eye which often represented the data trend better. Curve fitting was then applied to
two or more points on the visually fitted line. Two power functions were fitted to transport relations with a curved trend in log-log space, one to the steep initial increase and one to the upper, flattened part. For data presented as plots in log-linear or linear-linear scales, geometric (or arithmetic) mean values of $Q_b$ were visually estimated for several increments of $Q$ and a power function was then fitted to the estimated means. In all, 26 transport relations were derived from the sites sampled by the writers mainly in the Rocky Mountains and 70 transport relations were derived from datasets published for streams worldwide.

2.2.2 Calculating $q_{B,1.5}$: The cross-sectional, gravel transport rate associated with the $Q_{1.5}$ flow, $Q_{B,1.5}$, was determined for each dataset by solving Eq. 1 for $Q_{1.5}$. The unit gravel transport rate $q_{B,1.5}$ was obtained by dividing the predicted $Q_{B,1.5}$ by stream width $w_{1.5}$ and multiplying by a bias-correction factor $F_{bias}$ to counteract the inherent under-prediction of y-values from x-values in power functions (Eq. 2); i.e.,

$$q_{B,1.5} = a \cdot Q_{1.5}^{-b} / w_{1.5} \cdot F_{bias}$$

(Eq. 2)

Various approaches are possible to compute $F_{bias}$ (Hirsch et al., 1992); this study applied the one by Ferguson (1986, 1987) to most of the writers’ datasets. Bias-correction factors generally increase with data scatter and ranged from 1 to 3 for the writers’ study streams. Depending on a visual assessment of scatter in plotted data, values of 1.5 to 2.5 were assigned to datasets for which $F_{bias}$ was not provided.

2.2.3 Developing a suitable parameter to predict $q_{B,1.5}$: A suitable flow-based parameter that showed a close relation to $q_{B,1.5}$ needed to be devised to compare measured $Q_{B,1.5}$ between sites and predict $q_{B,1.5}$ for unsampled sites. Ryan (2007) has shown that, for a sequence of sites along a Rocky Mountain channel system, bankfull bedload transport rates increased in close correlation to the size of the basin area, $A$. The typically tight relation between $Q$ and $A$ within a stream system suggested that a similarly tight relation exists between $q_{B,1.5}$ and $Q_{1.5}$ or $q_{1.5}$. Plotted data from this study showed a relation between $q_{B,1.5}$ and $q_{1.5}$ (Figure 1a), and most data pairs fell into a central band three orders of magnitude wide. However, the large width of the central data field and its curved trend (in log-log space) that cannot be described by simple curve-fitting makes the relation of $q_{B,1.5}$ vs. $q_{1.5}$ not well suited for comparison and prediction of $q_{B,1.5}$, albeit that a power function can be fitted to the lower data branch representing mountain channels with $q_{1.5} < 1 \text{ m}^3/\text{m}^2 \cdot \text{s}$.

Bagnold’s (1977) stream power per unit width $\omega = \rho \cdot q \cdot S$, where $\rho$ is the fluid density, $q$ is the discharge per unit width, and $S$ is a reach-averaged channel gradient in m/m, is sometimes used for comparison of bedload transport relations ($Q_b$ vs. $\omega$) between streams (e.g., Martin and Church, 2000). However, $\omega$ was not a suitable parameter for the diverse streams compiled in this study: In the plotted relation of $Q_{B,1.5}$ vs. $\omega_{1.5}$ with data of all study sites, steep streams plotted to the right of lower-gradient streams (Figure 1b), suggesting that for the same stream power, low-gradient streams have much larger $q_{B,1.5}$ than steeper channels. The reason is an overly large numerical influence of stream gradient. In our data compilation, $S$ covered a 100-fold range (0.1 to 0.001 m/m) among mountain streams and controlled a study site’s $\omega_{1.5}$ value much more than $q_{1.5}$ which covered a 10-fold range (0.2 to 2 m$^2$/s). Besides, even among sites of similar channel gradients, the scatter of $q_{B,1.5}$ with $\omega_{1.5}$ was too wide to permit prediction of $q_{B,1.5}$.

Figure 1. Relation of $q_{B,1.5}$ vs. unit discharge $q_{1.5}$ (a) and vs. unit stream power $\omega_{1.5}$ (b). Streams are grouped by stream type.
Based on this experience, the writers developed a modified unit stream power expression \( \omega_{b,5}' \) that incorporated the promising parameter \( q_{1.5} \) (Figure 1a) and diminished the overly strong influence that \( S \) exerts on \( \omega_b \) (Figure 1b) by take the square root of \( S \) which balances the numerical influences of \( q_{1.5} \) and \( S \)

\[
\omega_{b,5}' = \rho \cdot q_{1.5} \cdot S^{0.5} \cdot \%D_{\text{sub}<8}
\]  

(Eq. 3)

Here, \( q_{1.5} \) is \( Q_{1.5} \) per unit width; \( S \) is square rooted to limit the range of its numerical values; and, \( \%D_{\text{sub}<8} \) is the percentage of subsurface fines <8 mm. Units are kg, m and s, while subsurface fines are entered as percent value (e.g., as 25 for 25%). Compared to Bagnold’s stream power \( \omega_b \) the lowered effect of \( S \) in the modified \( \omega' \) reflects the dissipation of a large portion of the flow energy in mountain streams. For this reason, Nitsche et al., (2011) had suggested using \( S \) as its square root to describe flow hydraulics in steep streams. The writers also note that common flow velocity relations (e.g., Manning and Chezy) relate mean velocity of open-channel flow directly to \( S^{0.5} \).

This study’s parameter \( \omega_{b,5}' \) includes a term for bed mobility: \( \%D_{\text{sub}<8} \) was added because the presence of sand and fine gravel in a streamedbed enhances particle mobility and transport rates of all particle sizes, including coarse gravel (Ikeda and Iseya, 1987; Wilcock et al., 2001; Wilcock and Kenworthy, 2002). In the data for this study, \( \%D_{\text{sub}<8} \) ranged from 12-82% and was found to be largely independent of hydraulic or channel geometry parameters but slightly positively related to surface sediment’s ratio of % fines <8 mm to \( D_{84}, \%D_{\text{sub}<8} = 45\left(D_{\text{surf}<8}/D_{84}\right)^{0.2}, r^2 = 0.41 \)

The \( \%D_{\text{sub}<8} \) is ideally determined from a cumulative grain-size distribution of large volumetric sediment samples. Sample collection techniques and necessary sample volumes are explained in Bunte and Abt (2001). For the writers’ study sites, \( \%D_{\text{sub}<8} \) was computed from detailed field samples and values of \( \%D_{\text{sub}<8} \) ranged between 16 and 34%, with a mean near 25%. Several datasets in the compilation likewise provided cumulative grain-size distributions for subsurface sediment.

If needed, the surface grain-size distribution served as a guide to estimate a value for \( \%D_{\text{sub}<8} \). Surface and subsurface size-distributions have similar coarse ends, and a subsurface distribution curve—although elevated—has a curvature that is typically similar to that of the surface distribution. Photos from the study site and Google Earth images give some indication of the relative abundance of fine surface sediment and hence suggest whether subsurface fines are scant or abundant. Also, the grain-size distribution of bedload collected near \( Q_{1.5} \) may represent the finer and central portion of the subsurface size distribution. A loose relation was noted between \( \%D_{\text{sub}<8} \) and channel type within the data compilation and those values may help to guide an estimate: \( \%D_{\text{sub}<8} \) was lowest in steep plane-bed streams (12-40%), slightly higher (15-45%) in step-pool channels, mountain torrents, and low-gradient plane-bed channels, and again slightly higher in pool-riffle channels (20-45%). Sand-rich gravel-bed streams had the highest values (50-80%).

2.2.4 Data grouping: For visual comparison among streams, plotted data of \( q_{B,1.5} \) vs. \( \omega_{b,5}' \) were grouped by channel type following the gradient-based classification proposed by Montgomery and Buffington (1997), but also noting other stream types. Separate symbols were used to differentiate between step-pool channels, steep plane-bed streams with occasional mini-steps, lower-gradient plane-bed streams with occasional or forced pool-riffle sequences, and pool-riffle channels. Those channel-type-specific symbols were then used with various color schemes to differentiate between subtypes of streams within the same gradient class: For example, low-gradient plane-beds with occasional pool-riffles contained three groups: 1. Relatively large Rocky Mountain channels sampled by the writers with less than desirable sample size, 2. Ephemeral desert streams, and 3. Sand-rich streams with notably large amounts of surface sand. Also marked as groups were large valley streams with gradients of 0.001 to 0.004 m/m draining mountain watersheds in the Alps, the Pacific NW, and British Columbia with basin areas 800-2100 km² and large foreland streams with gradients of 0.0003 to 0.0009 m/m and basin areas >6000 km². A second layer of grouping categorized mountain streams by geographical location. The study differentiated between the writers’ sites located mainly in the U.S. Rocky Mountains (CO, WY, MT), steep streams in the Pacific NW and British Columbia, as well as mountain streams in the European and New Zealand Alps, the Canadian Rockies, the Karakorum, the Chinese Yunnan Province in the SE Himalaya, and central Japan. The few streams not falling into any of the categories above were labeled “other”.

Based on this experience, the writers developed a modified unit stream power expression \( \omega_{b,5}' \) that incorporated the promising parameter \( q_{1.5} \) (Figure 1a) and diminished the overly strong influence that \( S \) exerts on \( \omega_b \) (Figure 1b) by take the square root of \( S \) which balances the numerical influences of \( q_{1.5} \) and \( S \)
### 3. Results

#### 3.1 Relation of unit gravel transport rates $q_{B,1.5}$ flow vs. modified stream power $\omega_{1.5}$

**3.1.1 Data from writers’ Rocky Mountain streams:** For the writers’ Rocky Mountain data, values of $q_{B,1.5}$ plotted vs. $\omega_{1.5}$ in log-log space showed a positive, straight trend. Most data fell within a central envelope two orders of magnitude wide (Figure 2). The few outlier data (transport rates below or above the central data envelope) were explainable based on the writers’ familiarity with their study sites: overly low values of $q_{B,1.5}$ resulted from upstream gravel entrapment behind beaver dams, woody debris, and within a large pool and also resulted from the limited competence of the $Q_{1.5}$ flow to mobilize beds in oversized cross-sections. By contrast, sediment release from a logjam into a stream that was already well supplied from a watershed mostly above tree-line resulted in an overly high value of $q_{B,1.5}$. This finding indicated that the streams within the envelope had neither extremely high nor extremely low $q_{B,1.5}$.

![Figure 2: Unit gravel transport rates $q_{B,1.5}$ for the $Q_{1.5}$ flow measured mainly with bedload traps and a large net-frame sampler in central Rocky Mountain streams and plotted vs. a modified stream power parameter $\omega_{1.5}$. Most of the data fall within the dashed envelope. Outlier data are annotated.](image)

Intrinsic natural variability due to intra-seasonal hysteresis and annually-variable sediment supply explained a data scatter at the writers’ sites over two orders of magnitude within the central envelope. For example, the bed of a steep plane-bed stream ran out of sediment supply at the end of a long and large high-flow season. Another example comes from a low-gradient plane-bed stream: the study site sampled across an active point bar produced higher $q_{B,1.5}$ than the site sampled at a pool-exit 10 m upstream during the same high-flow season. In both cases, $q_{B,1.5}$ varied by 3- to 20-fold within one season. Between-year differences in $q_{B,1.5}$ were even higher: Five of the writers’ sites were sampled over two high-flow seasons, and $q_{B,1.5}$ varied by factors of 3-100 between years.

The steady increase of $q_{B,1.5}$ with $\omega_{1.5}$ for the 26 data from Rocky Mountain streams that fell within the central data envelope (Figure 2) was expressed by a fitted power function

$$y = 1.13E-11x^{3.56}$$

with $R^2$ of 0.56

(Eq. 4)
This empirical function facilitates a rough estimate of \( q_{B,1.5} \) from a modified stream power parameter \( \omega_{1.5}' \) to within \( \pm \) an order of magnitude in central Rocky Mountain streams.

### 3.1.2 Data combined from Rocky Mountain and worldwide streams: Moderate sediment supply within the central data envelope

The 70 worldwide datasets were added to the plot of \( q_{B,1.5} \) vs. \( \omega_{1.5}' \) in Figure 2. Of the literature data, % fell into the data envelope that was extrapolated from the Rocky Mountain streams and slightly widened to a little over two orders of magnitude (Figure 3). Among the worldwide streams that fell within the envelope were high-elevation Alpine step-pool and plane-bed streams, pool-riffle streams in Canada, England, and northern Italy, sand-rich gravel-bed streams in the Pacific NW, Wyoming, and the Eastern U.S., a small step-pool stream in the interior of British Columbia, and even many of the large valley and foreland streams. The interpretation of “normal” sediment supply for values of \( q_{B,1.5} \) from Rocky Mountain streams within the central data envelope (Figure 2) was extended to the worldwide data because exceptionally high or low sediment supply could also be documented for worldwide sites falling above and below the central zone.

![Figure 3](image-url)

**Figure 3.** Unit gravel transport rates \( q_{B,1.5} \) plotted vs. a modified stream power parameter \( \omega_{1.5}' \): Most worldwide data fall into the data envelope extrapolated from the Rocky Mountain streams encircled in a dashed green line.

**Very high sediment supply** The few worldwide datasets of \( q_{B,1.5} \) vs. \( \omega_{1.5}' \) that plotted notably above the central data envelope included three mountain torrents: one was a steep pro-glacial stream draining a recently deglaciated valley in the Canadian Rockies (Nanson, 1974); another was a small torrent in China’s Yunnan Province in the SE Himalaya draining a highly anthropogenically disturbed catchment underlain by crumbly sedimentary lithology (Yu et al., 2009); and, the highly active Erlenbach gulch (Rickenmann, 2012) that is subject to heavy summer thunderstorms and drains a small catchment with unstable, creeping hillslopes in the Swiss Flysch zone (crumbly marine sediments). Exceptionally high gravel transport rates were also reported for a pool-riffle stream in the northern Montana Front Range where steep, ephemeral washes are incised into faulted sedimentary lithology. Flashy flows transport large amounts of coarse sediment and boulders from unstable headwaters to intermittent channels and on to perennial streams (Whitaker and Potts, 2007 a, b). A borderline-high sediment supply was produced in two ephemeral streams in the Negev desert (Reid et al. 1995, 1996; Powell et al., 1998; Laronne et al., 2003) and in a stream in the Austrian Alps located at the confluence of three highly productive, glacier-fed tributaries (Kreisler et al., 2016). In all of those streams, the very high transport rates during commonly occurring high-flow events were associated with enormous sediment supply from catchments that were either poorly vegetated, had naturally unstable lithology, or experienced major anthropogenic hillslope destabilization. These findings confirm the large role lithology plays in setting transport rates (Ryan 2007).
**Very low sediment supply** The worldwide data points that fell below the central data envelope included a small step-pool stream down an escarpment in agricultural land in southern Brazil (G. Merten, pers. comm.) where tobacco fields produced little gravel supply. An unexpectedly low \( q_{B,1.5} \) in a step-pool stream in the Chilean Andes was caused by an annually developing calcium carbonate crust that kept bed particles cemented during commonly occurring events (L. Mao, pers. comm.; Ravazzolo et al., 2019). Borderline-low transport rates were also measured in a low-gradient plane-bed stream with pool-riffles sequences in central British Columbia (Hassan and Church, 2001; Church and Hassan, 2005). Here, stone-ring bed-structures kept much of the cobble-bed channel stabilized during commonly occurring high-flow events. Several sites along a small step-pool stream in southern British Columbia also plotted within the lower zone. Here, numerous log steps retained sediment and dissipated flow energy (Green et al. 2013, 2014a, b). A stream in Utah, degraded to an urban ditch and cut off from its upstream sediment supply, also had extremely low transport rates (Hinton, 2012). In all of these streams, very low transport rates during commonly occurring high-flow events were caused by bed-material stabilization, as well as sediment storage and energy dissipation associated with log steps, absence of upstream supply as well as due to upstream sediment retention. Very low gravel transport rates at the \( Q_{1.5} \) flow were also measured in steep streams in subtropical environments. In central Japan (Uchida et al., 2018, Sakurai et al., 2015, Mitsunaga et al., 2015; Handa et al., 2013), typhoons cause multiple very large flood events each year that seem to leave little sediment available for transport during a \( Q_{1.5} \) event. Furthermore, \( q_{1.5} \) values are high (water yields \( Q_{1.5} / A \) are 10-20 and up to 100 times higher, respectively compared to the Alpine and Rocky Mountain streams in the data compilation), which makes \( \omega_{1.5}' \) values high and shifts plotted data for those sites towards the right side in Figure 3. Similarly, frequent large monsoon floods seem to sweep channels clear of mobile sediment in some large Karakorum streams (Palt, 2001). Those data suggest that the \( q_{B,1.5} \) vs. \( \omega_{1.5}' \) relation may shift downward for mountain regions with frequent high-intensity rainstorms.

### 3.1.3 Empirical transport relation for steep worldwide streams with no extreme conditions of sediment supply:

For the 64 datasets of worldwide streams that plotted within the central data envelope, a fitted power function yielded the regression relation

\[
q_{B,1.5} = 4.0 \times 10^{-12} \omega_{1.5}'^{3.7}, \quad r^2 = 0.80
\]  

(Eq. 5)

The regression function (Eq. 5) is generally similar to the one fitted to the writers’ Rocky Mountain data (Eq. 4), but has a higher \( r^2 \) because a wider range of \( \omega_{1.5}' \) and of more data. Study results show that unit gravel transport rates \( q_{B,1.5} \) are sufficiently closely related to \( \omega_{B,1.5}' \) to predict \( q_{B,1.5} \) using a simple power function to within ± an order of magnitude in gravel and cobble-bed streams when sediment supply is neither exceptionally low nor exceptionally high.

### 3.2 Prediction of gravel transport rates \( q_{B,1.5} \)

#### 3.2.1 From observation to explanation:

Evaluation of gravel transport rates that fell within, above, and below the central zone had indicated that notable watershed and channel processes needed to have happened for a measured \( q_{B,1.5} \) to fall above or below the central zone. Sites with \( q_{B,1.5} \) higher than in the central zone were associated with unstable hillslopes, high sediment supply and direct connectivity to the stream channel, whereas sites plotting below the central zone were associated with low rates of sediment supply or supply exhaustion, upstream sediment retention, bed stabilization and energy dissipation.

#### 3.2.2 From explanation to prediction:

The obvious connection of a site’s gravel transport rates \( q_{B,1.5} \) with sediment supply, delivery, retention, bed stability and energy dissipation can be used to guide estimation of \( q_{B,1.5} \) for unsampled streams. Aerial photography (Google Earth or other images) is useful to qualitatively assess the magnitude of a watershed’s sediment supply (e.g., from visible hillslope instability), the directness of hillslope-channel connections, sediment supply contributed by productive tributaries and active bank erosion, as well as the downstream gravel conveyance potential (e.g., its obstruction by lakes, ponds, log jams, and beaver dams). Closer to the study site, field visits can clarify if sediment has recently been retained by logjams and beaver dams (or was released therefrom). Site visits also can ascertain if repeated energy dissipation occurs on weirs, drop structures, and logs, and how much resistance to entrainment a channel bed may offer to common high-flow events (e.g., due to a coarse pavement, stone rings, or an oversized cross-section).
Once the necessary data have been compiled to compute $\omega_{1.5}'$ from Eq. 3 for an unsampled site, the assessment of a site’s watershed, channel conveyance, and study reach as producing or receiving unremarkable, very high or very low sediment supply suggests whether the $q_{B,1.5}$ for the study site with a specified $\omega_{1.5}'$ will fall into the central envelope, or above or below it. On a finer scale, estimates of $q_{B,1.5}$ (to within ± one order of magnitude around Eq. 4) inside the central zone may likewise be narrowed, and results from visual assessment of watershed, channel, and reach conditions may guide the decision whether a site’s $q_{B,1.5}$ might fall towards the upper border of the central envelope, the envelope’s central portion, or towards the envelope’s lower border. A study site’s classification into one of the three zones is not necessarily permanent. While the upper border may be more firm than the lower border, common natural variability may occasionally shift gravel transport rates from sites that had plotted within the central zone in one year across the border in other years.

### 3.3 Gravel concentrations and gravel yield

Other than by the parameter $q_{B,1.5}$, gravel transport intensity may also be expressed as gravel concentration (transport rates $Q_{B,1.5}/Q_{1.5}$ flow) or as gravel yield ($q_{B,1.5}/A$). The argument may be posed that the relative magnitude of transport rates at the $Q_{1.5}$ flow might be more meaningfully evaluated for transport rates that are related to the discharge or the basin area that produced them. To determine differences and suitability of those approaches, analyses described in Section 3.1 for unit gravel transport rates $q_{B,1.5}$ were likewise applied to gravel transport expressed in terms of $Q_{B,1.5}/Q_{1.5}$ and $q_{B,1.5}/A$.

#### 3.3.1 Relation of $Q_{B,1.5}/Q_{1.5}$ with $\omega_{1.5}'$

The plot of gravel concentration $Q_{B,1.5}/Q_{1.5}$ vs. $\omega_{1.5}'$ (Figure 4) looks quite similar to the plot of $q_{B,1.5}$ vs. $\omega_{1.5}'$ (Figure 3) with $2/3$ of the data falling into a central data zone and some data falling above and below. Most of the sites that had fallen within the central zone of the relation $q_{B,1.5}$ vs. $\omega_{1.5}'$ (Figure 3) likewise fell within the central zone of the relation $Q_{B,1.5}/Q_{1.5}$ vs. $\omega_{1.5}'$ and the vertical width of the central zone also extended over just slightly more than two orders of magnitude. Differences compared to the relation $q_{B,1.5}$ vs. $\omega_{1.5}'$ were that the ephemeral Negev streams and the Austrian stream near the confluence of three productive tributaries moved from the upper border well into the central data field. By contrast, along the lower border, all large foreland streams dropped out of the central zone, and only the better-supplied large valley streams remained within the central zone.

**Figure 4.** Gravel concentrations $Q_{B,1.5}/Q_{1.5}$ plotted vs. a modified stream power parameter $\omega_{1.5}'$: A distinct segregation into the three zones similar to Figure 3 is evident.
Overall, the relation of $Q_{B,1.5}/Q_{1.5}$ vs. $\omega_{1.5}'$ revealed a clear separation of gravel concentrations within the central zone from those that are extremely high and extremely low. A power function regression fitted to the data points in the central zone of $Q_{B,1.5}/Q_{1.5}$ vs. $\omega_{1.5}'$ yielded the equation

$$Q_{B,1.5}/Q_{1.5} = 8.7 \times 10^{-11} \omega_{1.5}'^{3.4}, r^2 = 0.76, n = 64$$  \hspace{1cm} \text{(Eq. 6)}$$

which was almost as steep and as tightly defined as Eq. 5.

It is not known whether the clearer segregation of the data in the plot of $Q_{B,1.5}/Q_{1.5}$ vs. $\omega_{1.5}'$ into the three zones is entirely inherent or somewhat incidental. The use of similar parameters, $Q_{1.5}$ and $q_{1.5}$ on the two axes may contribute to the zonal segregation. In any case, the plotted relation of $Q_{B,1.5}/Q_{1.5}$ vs. $\omega_{1.5}'$ confirmed the general classification of three zones of gravel transport: extremely high, moderate, and extremely low.

### 3.3.2 Prediction of $q_{B,bf}/A$ from $\omega_{1.5}'$:

The familiar segregation into the three zones was likewise evident in the plotted relation of $q_{B,1.5}/A$ vs. $\omega_{1.5}'$ (Figure 5). Most of the sites contained within the central zone in the relation of $q_{B,1.5}$ vs. $\omega_{1.5}'$ also populated the central zone in the relation of $q_{B,1.5}/A$ vs $\omega_{1.5}'$, and the central zone was likewise just slightly wider than two orders of magnitude. A power function regression is fitted to the cohort of sites within the central zone and yields the equation

$$q_{B,1.5}/A = 4.5 \times 10^{-15} \omega_{1.5}'^{4.2}, r^2 = 0.78, n = 54$$  \hspace{1cm} \text{(Eq. 7)}$$

However, the plot of $q_{B,1.5}/A$ vs. $\omega_{1.5}'$ sorted streams by their basin area size: streams with small basins generally plotted slightly higher than larger streams, while streams with large basin areas shifted downward. As a result, most of the large valley streams and all of the foreland streams dropped out of the central zone into the zone of extremely low gravel yield. This shift suggest that the relation $q_{B,1.5}/A$ vs. $\omega_{1.5}'$ in Eq. 7 is best applied to small mountain streams with basin areas less than about 200 m².

![Figure 5](image-url)

**Figure 5.** Unit gravel yield $q_{B,1.5}/A$ for the $Q_{1.5}$ flow plotted vs. a modified stream power parameter $\omega_{1.5}'$: A segregation into the three zones similar to Figure 3 is evident.

### 4. Summary and Discussion

This study compiled 96 gravel transport relations (measured by the writers in mainly Rocky Mountain streams and studies reported in the literature for streams worldwide) to produce a plotted relation be-
tween unit gravel transport rates for a commonly occurring high-flow event ($q_{B,1.5}$) vs. a modified stream power parameter ($\omega_{B,1.5}$) (Figure 3). The plot reveals a central data zone about two orders of magnitude wide within which the majority of the data fall. Variability of $q_{B,1.5}$ within that zone is attributed to common natural variability in sediment supply as well as to errors in measurements and computations. Within the central zone, $q_{B,1.5}$ increases with $\omega_{B,1.5}$ following a simple and well-defined ($r^2 = 0.8$) power function. The study revealed that for a specified value of $\omega_{B,1.5}$, the magnitude of measured $q_{B,1.5}$—and hence the zone into which a study site falls—is associated with the watershed’s and channel’s situation regarding sediment supply. This connection is instrumental in guiding an estimate of the magnitude of $q_{B,1.5}$.

To apply results from this study for estimating $q_{B,1.5}$ to an unsampled site, a user first computes $\omega_{B,1.5}$ (Eq. 3) for that site. A user then employs interpretation from aerial photography (e.g., Google Earth images) and field information to assess the watershed’s ability to generate gravel supply, the transfer of that supply from hillslopes to the channel, and the channel’s potential to convey or retain that sediment in order to arrive at a qualitative categorization of a site’s sediment supply as unremarkable, very high, or very low. With $\omega_{B,1.5}$ computed and the study site’s sediment supply situation categorized, Figure 3 can be consulted to graphically determine the most likely zone (central, high or low) for a study site’s estimate of $q_{B,1.5}$. Alternatively, a user may estimate a site’s gravel concentration $Q_{B,1.5}/\omega_{B,1.5}$ using Figure 4 or gravel yield $q_{B,1.5}/A$ using Figure 5. If a site’s unremarkable situation of sediment supply has already been established, Eqs. 5, 6, or 7 may be applied directly.

**Recommendation for using this study’s approach to estimating gravel transport rates.** A study site’s gravel transport rate is best estimated (or evaluated) by applying all three expression of gravel transport: unit gravel transport rates, gravel concentrations and gravel yield. Considering that the database for this empirical study stems mainly from small and midsized streams in basins with temperate climates and from largely unaltered channels, this study’s approach is foremost intended for streams in those climates.

**Is differentiation of the magnitude of gravel transport into three zones real?** Several arguments support the visual segregation of the relations between $q_{B,1.5}$ and $\omega_{B,1.5}$ into the three zones and that the segregation reflects actual differences in gravel transport and sediment supply. 1) The outline of the central zone was initially determined from the writers’ stream sites for which the sediment supply situation in the year of sampling was well known (Figure 2). 2) The trend of the central zone extrapolated from the writers’ Rocky Mountain sites holds for plotted relations of $q_{B,1.5}$ vs. $\omega_{B,1.5}$ from many of the worldwide streams (Figure 3), and the extremely high or low sediment supply situations for worldwide datasets falling below or above the central zone are explainable from information provided in the study or from an assessment of a watershed’s and channel’s situation of sediment supply. 3) The segregation of plotted relations of gravel transport vs. $\omega_{B,1.5}$ into three zones (central, above and below) appears to be general—holding regardless of whether gravel transport is expressed in terms of unit transport rates (Figure 3), gravel concentration (Figure 4), gravel yield (Figure 5), or simply as a relation between $q_{B,1.5}$ and $q_{1.5}$ (Figure 1a). 4) The segregation is numerically robust in that the number of sites within each zone remains similar for all transport expressions: 4-7% of the data are above the central zone and 20-30 % of the data below. And even the zones’ data cohorts remain largely similar for the various expressions of gravel transport: The only shifters between zones are sites with very high sediment supply, as well as large foreland and large valley streams.

**Systematic difference between stream types?** Within the central zone, the magnitude of $q_{B,1.5}$ was not determined by stream type (and hence not by stream gradient). The exceptions are mountain torrents and ephemeral streams, both of which exhibited very large transport rates at the $Q_{1.5}$ flow. Similarly, a stream’s runoff yield, $Q_{1.5}/A$, appears to exert only a small influence on $q_{B,0.5}$. Within the central zone, however, sites close to the tree-line tended to have larger $q_{B,1.5}$ values than do sites in fully forested basins.

**The effect of data errors on the plotting position of $q_{B,1.5}$ vs $\omega_{B,1.5}$**. Potential errors in values estimated for $q_{1.5}$ from measured field data cannot be quantified, because true values of $q_{1.5}$ are unknown. Errors in $q_{1.5}$ are assumed to be below 20% for most of the sites, but might reach 50% for a few sites with scant hydrological information. Subsequent errors in $\omega_{B,1.5}$ progress linearly because $q_{1.5}$ is a simple multiplier in $\omega_{B,1.5}$. By contrast, errors in the estimates of a site’s $q_{1.5}$ cause misprediction in $q_{B,1.5}$ that increase
with the steepness of a stream’s transport relations. For a rating curve exponent of 6, errors in $q_{1.5}$ of ±20% and ±50% results in 3-4 fold misprediction of $q_{B,1.5}$ and more than an order of magnitude, respectively. For a rating curve exponent of 12, errors in $q_{1.5}$ by ±20% and ±50% mispredict $q_{B,1.5}$ by about one order of magnitude and 2-3 orders of magnitude, respectively. Being aware of the potential errors, great care was taken in determining $q_{1.5}$ and in accurately fitting transport relations.

While an error in $q_{1.5}$ may greatly affect a site’s value of $q_{B,1.5}$, the resulting error in the plotted relation of $q_{B,1.5}$ vs. $o_{b,1.5}$ is typically less severe because any error in $q_{1.5}$ affects both $q_{B,1.5}$ and $o_{b,1.5}$ by shifting a plotted data point diagonally. The increase of $q_{B,1.5}$ with $o_{b,1.5}$ followed a power law with an exponent of 3.7 (Eq. 5). Consequently, for gravel transport relations with exponents in that range, any error in $q_{1.5}$ shifts a data point diagonally within its original zone. For flatter or steeper rating curves, the shift is still diagonal but it may transfer a data point into a neighboring transport zone.

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5. References


