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The effect of flow data resolution on sediment yield estimation and channel design

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SUMMARY

The decision to use either daily-averaged or sub-daily streamflow records has the potential to impact the calculation of sediment transport metrics and stream channel design. Using bedload and suspended load sediment transport measurements collected at 138 sites across the United States, we calculated the effective discharge, sediment yield, and half-load discharge using sediment rating curves over long time periods (median record length = 24 years) with both daily-averaged and sub-daily streamflow records. A comparison of sediment transport metrics calculated with both daily-average and sub-daily stream flow data at each site showed that daily-averaged flow data do not adequately represent the magnitude of high stream flows at hydrologically flashy sites. Daily-average stream flow data cause an underestimation of sediment transport and sediment yield (including the half-load discharge) at flashy sites. The degree of underestimation was correlated with the level of flashiness and the exponent of the sediment rating curve. No consistent relationship between the use of either daily-average or sub-daily streamflow data and the resultant effective discharge was found. When used in channel design, computed sediment transport metrics may have errors due to flow data resolution, which can propagate into design slope calculations which, if implemented, could lead to unwanted aggradation or degradation in the design channel. This analysis illustrates the importance of using sub-daily flow data in the calculation of sediment yield in urbanizing or otherwise flashy watersheds. Furthermore, this analysis provides practical charts for estimating and correcting these types of underestimation errors commonly incurred in sediment yield calculations.

1. Introduction

Current practice in stable channel design focuses on a single “channel forming” discharge that is assumed to be the flow primarily responsible for performing work, transporting sediment, and shaping channel geometry over a period of years (Soar and Thorne, 2001; Doyle et al., 2007). Coupling continuous flow series with sediment-transport relationships to quantify the combined effects of flow and sediment regime using magnitude–frequency analysis (Wolman and Miller, 1960) is increasingly used to compute physically based estimates of channel forming flows, such as the effective discharge (e.g., Shields et al., 2003; Doyle et al., 2007) or the half-load discharge (Sholtes and Bledsoe, 2016).

Sediment yield estimates used in alluvial channel design are calculated from two types of input data: relations between stream discharge and the sediment transport rate, and flow frequency distributions. The accuracy of a sediment yield calculation will therefore be determined by the errors or uncertainties in these two components. The relationship between discharge and sediment transport is often characterized via a sediment rating curve, which is an empirical best-fit power function relating paired instantaneous streamflow and sediment discharge measurements (Walling, 1977). Errors and limitations of sediment rating curves have been extensively studied: for example, they can be imperfect estimators of sediment transport rates due to statistical fitting errors (Ferguson, 1987), storm event hysteresis (Walling, 1977; Moog and Whiting, 1998), non-stationarity in sediment supply over time (Asselman, 2000), and fluctuations inherent to sediment transport (e.g., Kuhnle and Southard, 1988; Curran et al., 2015). Uncertainty in sediment yield calculations due to the flow frequency distribution characteristics, however, has received little attention. In particular, it is not known how the resolution of a streamflow dataset (i.e., daily-averaged vs. sub-daily measurements) can affect sediment yield calculations.

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Nomenclature

a	sediment rating curve best fit coefficient
b	sediment rating curve best fit exponent, logarithmic slope of sediment transport
D_{50}	median grain size (mm)
D_{84}	84th percentile grain size (mm)
p	probability of rejecting the null hypothesis when the null hypothesis is true
Q_{Eff}	effective discharge $\left(\frac{m^3}{s}\right)$
$Q_{Eff\text{-}Daily}$	effective discharge computed with daily-averaged flow data $\left(\frac{m^3}{s}\right)$
$Q_{Eff\text{-}Sub}$	effective discharge computed with sub-daily flow data $\left(\frac{m^3}{s}\right)$
Q_{s50}	discharge below which 50% of bed material load is transported $\left(\frac{m^3}{s}\right)$
$Q_{s50\text{-}Daily}$	discharge below which 50% of bed material load is transported, computed from daily flow data $\left(\frac{m^3}{s}\right)$
$Q_{s50\text{-}Sub}$	discharge below which 50% of bed material load is transported, computed from sub-daily flow data $\left(\frac{m^3}{s}\right)$
RB	Richards–Baker flashiness index (Baker et al., 2004)
S_{Daily}	channel design slope computed from daily flow data
S_{Sub}	channel design slope computed from sub-daily flow data
SY	sediment yield (m^3)
SY_{Daily}	sediment yield computed with daily flow data (m^3)
SY_{Sub}	sediment yield computed with sub-daily flow data (m^3)

The use of daily-averaged streamflow records paired with sediment rating curves to calculate sediment yield implicitly assumes that this resolution of data adequately represents the flow regime. However, studies have shown that small (Ågren et al., 2007), urban (Graf, 1977; Walsh et al., 2005), and arid watersheds (Allan and Castillo, 2007) can exhibit rapid short-term variations in streamflow during runoff events. This type of streamflow behavior is termed “flashy.” In flashy watersheds, flows that transport high sediment loads may happen infrequently and for very brief periods of time; in these situations, daily-averaged flow data may not adequately capture the magnitude of discharge most important for sediment transport.

It was recognized long ago that using sediment rating curves with daily-averaged flow data could cause errors in the computation of sediment discharge if the daily-average stream discharge is not representative of the flow rate throughout the day (Colby, 1956). Because sediment discharge is nonlinearly related to stream discharge, small errors in the magnitude of streamflow may cause large errors in the estimation of sediment transport. However, quantitative relationships between flow regime characteristics such as flashiness, characteristics of the sediment transport rating curve, and the relative error in sediment transport metrics due to flow data resolution have not been established. We hypothesize that errors in sediment transport and yield calculations based on daily-average flow data systematically increase with stream flashiness.

There have been few studies exploring how flow data resolution can affect sediment yield calculations. A study of six watersheds in East Devon, England showed that sediment yield calculations from daily flow records could vary by up to 10% from those made with instantaneous records (Walling, 1977). A study of small to medium-size watersheds (smaller than 620 km^2) of the Yazoo River basin in Northwest Mississippi revealed that sediment yield curves created from daily-averaged flow data can deviate from 15-min sediment yield curves by more than 100% (Hendon, 1995). This was because the highest discharges, occurring less than 3% of the time, were smoothed out in the daily-averaged data. In another study from the same basin, use of daily-average flow data were found to underpredict sand yield by 51% and total suspended sediment yield by 59% (Dubler, 1997). To the best of our knowledge, the effect of flow data resolution on sediment transport calculations has not been investigated anywhere else.

In this paper, we explore the effect of flow data resolution on sediment transport metrics for both bedload and suspended load transport for fine and coarse bed rivers across the United States. The objectives of this paper are: (i) to quantify the effect of flow data resolution (daily-averaged and sub-daily) on sediment yield calculations; (ii) to investigate the factors such as hydrologic flashiness or sediment rating curve characteristics that most strongly influence the error in calculating sediment yield metrics so that we may better understand under what conditions it is important to have sub-daily flow data, (iii) to provide readers the necessary tools to self-identify situations in which using daily-averaged flow data for sediment transport calculations is, or is not acceptable based on their own specifications; and (iv) to investigate the potential impacts on channel design parameters when daily-averaged flows are used in situations where sub-daily flows are more appropriate.

2. Methods

2.1. Data selection

This analysis draws on sediment transport data and flow records that were assembled for a related study concerning the magnitude and frequency of sediment transport in U.S. streams and rivers (Sholtes, 2015). Sites used in this analysis have >15 measurements of sediment load and instantaneous discharge collected adjacent to a stream gage with a long term record (median record length = 24 years) of daily and sub-daily discharge data. In total, 39 sites with bedload data and 99 sites with suspended sand load data were included in this analysis (Fig. 1).

The sites cover a wide range of the conterminous United States and represent drainage areas ranging from approximately 10 to 2,500,000 km^2. Basins were chosen such that a wide range of flow regimes would be analyzed including flashy and non-flashy systems. Summary information for sites used in the present study can be found in Tables S1 and S2 in the supplementary materials.

All bedload data were collected using Helley-Smith bedload samplers as this type of sampler has been the most widely used within the U.S., and the vast majority of existing bedload data were collected with this device (USFS, 2014a,b). Suspended load data were retrieved from the USGS Sediment Data Portal (http://cida.usgs.gov/sediment), an on-line database of suspended sediment measurements for sites across the U.S. Bedload data are used to represent sediment transport in coarse bed rivers with median bed material grain sizes >4 mm (gravel and larger) at sampling sites. Suspended sand load (>0.0625 mm) measurements are used to represent sediment transport in sand bed rivers with median bed material grain sizes ⩽1 mm. These sites are referred to as