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Estimating Sand Bedload in Rivers by Tracking Dunes: a comparison of methods based on bed elevation time-series

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Abstract. Quantifying bedload transport is paramount to the effective management of rivers with sand or gravel-dominated bed material. However, a practical and scalable field methodology for reliably estimating bedload remains elusive. A popular approach involves calculating transport from the geometry and celerity of migrating bedforms, extracted from time-series of bed elevation profiles acquired using echosounders. Various echosounder sampling methodologies of how to extract bed elevations profiles exist. Using two sets of repeat multibeam sonar surveys with large spatio-temporal resolution and coverage, we compute bedload using three field techniques (one actual and two simulated) for acquiring bed elevation profiles: repeat multi-, single-, and multiple single-beam sonar. Significant differences in flux arise between repeat multibeam and single beam sonar. Mulitbeam and multiple single beam sonar systems can potentially yield comparable results, but the latter relies on knowledge of bedform geometries and flow that collectively inform optimal beam spacing and sampling rate. These results serve to guide design of optimal sampling, and for comparing transport estimates from different sonar configurations.

1 Introduction

Bedload is usually a significant proportion of total load in rivers with sand and/or gravel-dominated bed material, and the relative importance of suspended load and bedload often changes with flow and the location within the channel (e.g. **?**). Whereas instrumentation and protocols for sampling suspended sediment loads are relatively well established (e.g. Nolan et al., 2005; Wren et al., 2000; Edwards and Glysson, 1999), reliable estimates of bedload are more difficult to obtain because bedload in transport is difficult to sample directly (e.g. Emmett, 1980; Gomez, 1991), define (e.g. Church, 2006; Yang, 1986), or estimate with empirical formulas (e.g. Van Rijn, 1984; Martin and Church, 2000). Therefore, the effectiveness of sediment management in river systems is often predicated on the accuracy and representativeness of available bedload measurements.

Reliable estimates of bedload transport have been shown to result from application of the Exner equation (Simons et al., 1965; Engel and Lau, 1980) to time-series of bed elevation profiles (Simons et al., 1965; Van Den Berg, 1987; Dinehart, 2002; Villard and Church, 2003; Wilbers and Ten Brinke, 2003; Claude et al., 2012; Guala et al., 2014) acquired with an echosounder.

https://doi.org/10.5194/esurf-2019-38
Preprint. Discussion started: 19 August 2019

Simons et al. (1965) first showed that bedload flux can be estimated by tracking the average celerity, V_c, of the downstream migration of dunes with a known average height, H, and average length, λ. These variables are averaged over a field of dunes to satisfy the necessary assumptions that suspended sediment load, q_s, is in equilibrium ($d_{qs}/dx = 0$), and with continuity of mass ($d_{qb}/dx + d\eta/dt = 0$), where x and η are downstream distance and bed elevation, respectively (Simons et al., 1965). The Simons et al. (1965) approach therefore quantifies only the first-order bedload flux due to dune translation, not accounting for any exchanges in bed material load between suspended and bedload fractions that deform the dune and may contribute to net transport (McElroy and Mohrig, 2009).

Complicating matters, however, is the inherent variability of bedform size a shape in natural river systems (Bradley and Venditti, 2017). Sediment and water discharge conditions, vary continuously in natural rivers causing bed morphology to be out of equilibrium with prevailing flow conditions. Numerous field studies suggest that bedform disequilibrium is likely the norm rather than an exception in natural river systems (e.g., Frings and Kleinhans, 2008; Julien et al., 2002; Ten Brinke et al., 2009; Wilbers and Ten Brinke, 2003; Fielding et al., 2009). Even with these complications, bedload flux estimated from translating dunes remains one of the most accurate bedload estimate techniques for sand-bedded rivers and as such bed elevation measurements are of great importance.

In practice, bed elevation profiles might be acquired in three ways using echosounders: repeat multibeam, single-beam, and multiple single-beam sonar (Fig. 1A). Repeat multibeam measures a spatially extensive three-dimensional bed, $\eta(x,y,t)$, from a moving vessel, from which it is possible to independently and simultaneously estimate V_c, H, and λ. Single beam systems measure a one-dimensional bed, $\eta(t)$, at a single (x,y) location using a stationary (fixed reference frame) sonar. Single-beam echosounder have also been used to acquire data from a moving vessel (specifically for longitudinal profiles in shallow environments). The study presented herein does not address bed elevation profiles and resulting flux estimates calculated from moving vessel single beam methods. Lastly, multiple single-beam measures a spatially limited three-dimensional bed, $\eta(x,y,t)$, at a few (x,y) locations using stationary sonar. All three sampling methodologies have been and are currently employed to collect bed elevation data in experimental (Blom et al., 2003; Van der Mark et al., 2008; Guala et al., 2014; Curran et al., 2015), fluvial (Simons et al., 1965; Ten Brinke et al., 1999; Ashworth et al., 2000; Julien et al., 2002; Parsons et al., 2005; Gaeuman and Jacobson, 2007; Nittrouer et al., 2008; Claude et al., 2012; Shugar et al., 2010; Rodrigues et al., 2015; Wintenberger et al., 2015; Huizinga, 2016; Kaplinski et al., 2017; Buscombe et al., 2017; Hackney et al., 2018), and estuarine/coastal environments (Villard and Church, 2003; Hoekstra et al., 2004; Schmitt and Mitchell, 2014).

There are practical benefits and drawbacks to each data collection method. Repeat multibeam is spatially extensive, but relatively expensive, only practical in relatively deep, safely navigable rivers, and limited in temporal coverage. Therefore, the use of in situ stationary echosounders (also called altimeters, here referred to as single beam and multiple single beam systems) is becoming an increasingly popular alternative (Gray et al., 2010). These systems are especially useful in shallow water, are less expensive than multibeam systems, and generating longer time-series (e.g. Moulton et al., 2014). However, only measuring the bed elevation at a single location means it is not possible to resolve V_c, H, and λ simultaneously. This has implications for bedload estimates that are explored in this paper.

https://doi.org/10.5194/esurf-2019-38
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Since different methodologies may be employed to collect bed elevation profiles, and thus calculate bedload transport rates, it is important that resulting bedload flux estimates are compared to test for consistency. Do differences in sampling methodology cause systematic differences in bed elevation profiles and bedload flux estimates? Are different sampling methods equally able to measure/account for bedform disequilibrium dynamics? How does bedform disequilibrium affect the bed elevation measurements made by different types of echosounders?

Presently, it is unclear how differences in bed elevation data acquired with different methodologies translate to the fidelity with which dune migration is captured, and finally to bedload transport estimates. Furthermore, multibeam, single beam, and multiple single beam datasets do not generally exist in the same location and time, making direct comparison of these datasets difficult. In order to examine these issues, we establish a virtual experiment using a repeat multibeam dataset to directly compare bedload transport estimates calculated from bed elevation profiles extracted to mimic the three different field survey methodologies outlined above.

2 Methods

2.1 Study Area and Survey Data

We use an extensive repeat multibeam dataset consisting of bed elevation from a large area of migrating dunes at high spatio-temporal resolution. Data come from a approx. 300 m long by 40 m wide reach upstream of the Diamond Creek USGS gage site on the Colorado River in Grand Canyon National Park (Fig. 1B, 1C), where flows are regulated by releases through Glen Canyon Dam 385 km upstream. We simulate data from simultaneous single beam and multiple single beam deployments by extracting time-series of bed elevations from the repeat multibeam datasets (Fig. 1D). This ‘virtual echosounder’ experiment allows us to directly compare flux estimates from all three methodologies. We assess the relative accuracy of the single beam and multiple single beam techniques at estimating bedload transport compared to repeat multibeam-derived bedload, and suggest practical guidelines for developing sampling and processing protocols that maximize accuracy.

Repeat multibeam surveys were collected at two different discharges (Fig. 2A) from just upstream of the Diamond Creek USGS gage site (Fig. 1C). All bathymetric data were collected using a Teledyne-Reson 7125 multibeam echosounder, with sensor attitudes provided by a vessel-mounted inertial navigation system, and positions telemetered to the survey vessel at 20 Hz using a robotic total station situated onshore on monumented control. Data were collected with a 50% overlap between adjacent sweeps, providing up to 1000 individual soundings per meter-squared. Each sounding was edited manually. Further details of this system, survey, and processing methods are given by Buscombe et al. (2014; 2017) and Kaplinski et al. (2017). The channel bed was entirely composed of fine to medium sand with no gravel patches (Buscombe et al., 2017). At each discharge, data were collected every 6-10 minutes for 12 hours. A digital elevation model of the riverbed was produced for each survey, using coincident 0.25x0.25 m grids. The March 2015 (around 283 m^3s^{-1}) and July 2015 (around 566 m^3s^{-1})repeat multibeam surveys occured during mostly increasing and decreasing hydrographs, respectively(Fig. 2A). The precision of the repeat surveys was high, with mean cell elevation standard deviation of 0.012m computed over rocks known to be immobile (Kaplinski et al., 2017).

https://doi.org/10.5194/esurf-2019-38
Preprint. Discussion started: 19 August 2019

Earth Surface Dynamics Discussions

2.2 Extraction of Bed Elevation Profiles

A 35 x 30 m subsection in approximately the middle of the area surveyed by the repeat multibeam was selected for detailed bedload analyses using repeat multibeam, single beam, and multiple single beam bed elevation profiles (Fig. 1C). This subsection was then divided into 40 different repeat multibeam bed elevation profiles (8.67 m in length, 3.67 m lateral spacing from one another; Fig. 1D) for March and 20 different repeat multibeam bed elevation profiles for July (17.34 m in length, 3.67 m lateral spacing from one another; Fig. 1D). The length of the bed elevation profiles was determined by considering the maximum dune wavelength. All repeat multibeam bed elevation profiles were detrended using the bedform tracking tool (BTT) developed by van der Mark et al. (2008). This tool detrends each BEP using a weighted moving average and extracts bedform height and wavelength data. This produced 2,720 individual repeat multibeam bedload transport estimates (and daily averages from the 40 bed elevation profiles) for March and 1,740 individual bedload transport estimates (and 20 daily averages) for July. Whereas repeat multibeam analyses can be carried out in two dimensions (Nittrouer et al., 2008; Abraham and Pratt, 2010; Abraham et al., 2011; Shelley et al., 2013), analyses were deliberately carried out using one-dimensional transects oriented with flow direction, so any anisotropic effects in flux (caused by dunes not aligned perpendicular to the flow) affected repeat multibeam, single beam and multiple single beam results equally. We have chosen not to incorporate the ISDOTTv2 dune differencing method (Abraham and Pratt, 2010; Abraham et al., 2011; Shelley et al., 2013) into the analyses presented herein as the resources to do so are not currently publicly available. We do, however, incorporate the missing triangles correction formulated by Shelley et al. (2013) into our calculations of bedload flux (see section 2.3, Equation 2).

Virtual single beam and multiple single beam echosounders were placed at the downstream end of each repeat multibeam BEP (Fig. 1D). multiple single beams have four virtual beams, one of which is the same beam location as the single beam virtual echosounders. Two different beam spacings were explored: 1) 0m-0.56m-1.16m-1.74m and 2) 0m-1.74m-3.48m-5.22m.

2.3 Calculating Bedload Transport

Bedload transport, q_b (m^3s^{-1}), was calculated using the Simons et al. (1965) formulation based on the two-dimensional Exner equation (Paola and Voller, 2005) for bed sediment mass conservation, assuming triangular dunes:

$$q_b = (1-p)V_c\frac{H}{2} - q_e - q_0 \tag{1}$$

where p is the porosity of the sand (0.35 was used here) and q_0 is a constant of integration (set to zero here; see McElroy and Mohrig (2009) for a discussion of the potential physical meaning of this term). The original formulation of (1) has been validated and extended by numerous studies (e.g. Willis and Kennedy, 1975; Engel and Lau, 1980; Havinga, 1983), most recently by Shelley et al. (2013) who proposed the addition of the q_e term, defined as:

$$q_e = \frac{V_c^2\Delta tH}{2\lambda} \tag{2}$$

where Δt is the change in time between successive surveys. Note that Eq. (1) is averaged over a field of dunes.

https://doi.org/10.5194/esurf-2019-38
Preprint. Discussion started: 19 August 2019

Earth Surface Dynamics Discussions Open Access EGU

The primary variables in the above equations are calculated differently for each type of bed elevation profile. For repeat multibeam, H and λ are calculated directly using the BTT. V_c is calculated using a cross-correlation of two consecutive bed elevation profiles (McElroy and Mohrig, 2009; Engel and Lau, 1980).

Single beam data consists of time-varying elevation only (Fig. 1A, 1F) therefore λ must be estimated independently. This might be done by measuring dune wavelengths in the field (for example, by wading, SCUBA, or using a boat-mounted sonar or ADCP) while installing or maintaining the echosounder. To simulate such an exercise, we use the daily average wavelength calculated by the BTT from the repeat multibeam survey directly upstream of the virtual single beam echosounder. Celerity (V_c) is:

$$V_c = \frac{\lambda'}{T} \tag{3}$$

where T is the period, and λ' is the estimated average wavelength.

For multiple single beam data, average period and height can be measured directly from the bed elevation profiles, whereas (V_c) may be estimated in one of three different ways. The first, “original method", is the same as Eq. (3), in which each beam is treated as a separate BEP to produce four estimates of transport that are then averaged. The second “cross-correlation method" is to use a cross-correlation of bed elevation profiles measured by two different beams to find the spatial offset or ‘lag’, l, between translated dunes:

$$V_c = \frac{D}{l * \Delta t} \tag{4}$$

where D is the distance between sensors. In a field situation, this is constrained by practical considerations, but here we are free to vary D to evaluate its effects. This method produces six estimates of bedload transport (from six pairs of four beams), as does the third, “manual method", in which velocity is:

$$V_c = \frac{D}{t_{m2} - t_{m1}} \tag{5}$$

where t_{m1} and t_{m2} are manually picked times at which a crest appears at each beam.

2.4 Sinusoid Model of Growing and Shrinking Bedforms

To test the affects of bedform disequilibrium (i.e. adjustment of bedform height and length to changing flow conditions), a simple sinusoid model was used to simulate time-varying dune height and wavelength. Each detrended bed elevation series was approximated by:

$$\eta = A\sin(B + Cx) \tag{6}$$

Dune growth/decay was controlled by varying A (amplitude) and C (wavelength). Dune translation was controlled by B (shift). Dune wavelength was estimated from dune height according to the regressions of the relationship between bedform height and wavelength for each survey day (Figure 2C). Using Eq. (6), sinusoid single beam bed elevation profiles are constructed from the synthetic elevation series, η, at a single location, x. These profiles were then used to calculate synthetic single beam bedload

https://doi.org/10.5194/esurf-2019-38
Preprint. Discussion started: 19 August 2019

transport estimates using Eq. (1) and (3). The average λ and H were used in these calculations to replicate the methods used for the virtual echosounder experiment. Synthetic repeat multibeam bedload transport rates are then calculated using Eq. (1).

3 Results

3.1 Dune Field Characteristics

Bedform height (wavelength) averaged 0.17m (2.38m) and 0.36m (5.1m) in March and July, respectively. Dune geometry was highly variable during both survey days, with standard deviations of bedform height (wavelength) of 0.05m (0.4m) in March and 0.2m (2.7m) in July. Discharge along the Colorado River in Grand Canyon fluctuates daily as a result of daily release flows from Glen Canyon Dam. In response to changes in discharge, bedform size almost doubled over the course of the survey in March and almost halved over the course of the survey in July (Fig. 2B). Due to the greater discharge, the bedforms in July are larger in height and wavelength (Fig. 2C) compared to those in March. A space-time plot of bed elevations shows bedform heights and wavelengths increasing over the duration of sampling in March (Figure 2D). Bedform crest traces become less frequent as bedform troughs deepen. In contract, a space time plot of bed elevations in July shows bedfrom heights and wavelengths decreasing throughout the survey period (Figure 2D).

3.2 Repeat Multibeam v. Single Beam

We consider the repeat multibeam-derived bedload estimates to be the most accurate because the superior spatio-temporal coverage of these data allow for simultaneous resolution of V_c, H, and λ. Single beam-derived daily bedload transport rates are underestimated relative to repeat multibeam in March, and overestimated in July (Fig. 2E). This could be caused either by mischaracterization of V_c, H, or λ in either repeat multibeam or single beam calculations, or in both.

The most likely source of error in the repeat multibeam calculations occurs when calculating V_c. To investigate whether cross-correlation correctly measured translation of dunes, l was manually calculated from repeat multibeam bed elevation profiles and then used to calculate bedform celerity. This showed that cross-correlation-derived V_c were underestimated in both March and July (Fig. 3A). This underestimation is much larger in July, when dunes were adjusting to decreasing flow conditions and deforming at a greater rate. This result indicates that caution should be exercised when using cross-correlation to derive V_c, especially during higher transport stages. The regressions between manual and cross-correlation computed V_c (Fig. 6) are used to calculate a lag-corrected celerity and lag-corrected bedload transport rates repeat multibeam data (Fig. 5). Correcting repeat multibeam estimates for cross-correlation lag errors results in 1.6% and 33.9% error for March and July, respectively. Percent error will be expressed relative to repeat multibeam-corrected lag flux estimates for the remainder of this paper.

Even with the lag-correction applied, discrepancies exist between repeat multibeam and single beam flux estimates due to errors estimating V_c from estimated wavelength and observed period. In March, period computed from single beam data is

Earth Surface Dynamics Discussions Open Access EGU

overestimated relative to repeat multibeam period, causing V_c, and therefore transport, to be underestimated. The opposite is true for the July data (Fig. 3B).

These discrepancies in observed period are likely linked to the bed responding rapidly to unsteady flows during each survey (Fig. 2A), with changes in discharge causing commensurate changes in H (Fig. 2B) and λ (Fig. 2C). This suggests that dunes in disequilibrium (i.e. growing/shrinking) apparently distort the period observed in the single beam data, which would invalidate the assumption made in Eq. (3) that the daily average wavelength (or any invariant measure of wavelength) is representative.

3.3 Single Beam Correction from Sinusoid Model

To test the above hypothesis, synthetic repeat multibeam and single beam flux estimates calculated from the growing/shrinking sinusoid models are compared. Single beam bed elevation profiles of growing and shrinking sinusoids display significantly different distributions of period compared to the assumption of constant bedform wavelength (Fig. 3C). When bedforms are in disequilirbium the period recored by the signle beam profile changes to either be longer or shorter depending on whether the dunes are growing or shrinking, which effects bedload transport measurements. As dunes grow or shrink, the ratio of synthetic repeat multibeam to synthetic single beam bedload transport increases or decreases, respectively. The maximum sinusoid repeat multibeam-to-single beam ratio for growing (shrinking) dunes is 1.2 (0.75). Applying these ratios as correction factors to the single beam estimates generates sine-corrected single beam transport estimates (Fig. 2E), resulting in a decrease of the discrepancy between repeat multibeam and single beam derived bedload from 45.3% to 27.7% in March and from 38.9% to 10.7% in July.

3.4 Repeat Multibeam v. Multiple Single Beam

Another potential practical solution to minimizing the distortion of period in single beam surveys is to use a multiple single beam echosounders in a spatial array (Figure 1). By increasing the spatial resolution of bed elevation data, multiple estimates of bedload may be obtained, as well as multiple options for computing V_c (Eq. (3) through (5)), two of which (Eq. (4) and (5)) do not require a priori estimation of (λ'). We expect the period recorded by each beam to be similarly affected by growing/shrinking dunes as were the single beam periods. We therefore apply the same sine correction from above to multiple single beam flux estimates calculated with the “original method". Fig. 4A shows these results for the beam spacing of 0, 0.56, -1.16, and -1.74 m for the three methods for computing celerity, and Fig. 4B shows the bedload transport estimates using a larger beam spacing and Eq. (5) only. The original method of calculating celerity (Eq. (3)) produces an average percent error of 13.3% and 15.8% in March and July, respectively; suggesting that increasing the number of beams and incorporating a sinusoid correction can mitigate discrepancies with repeat multibeam estimates.

The cross-correlation method (Eq. (4)) systematically over-estimates bedload transport in both March (43.4% error) and July (108.4% error), suggesting that the lag is systematically underestimated, and hence overestimating celerity. The manual method (Eq. (5)) yields a small mismatch between multiple single beam and repeat multibeam derived bedload in March (1.3% error) but a 62.9% error in July. This could be related to beam spacing, because the bedforms (and bedload mismatches) in the July data are much larger than those in March. This could cause greater celerity because only between 10 and 30% of the

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Preprint. Discussion started: 19 August 2019

Earth Surface Dynamics Discussions Open Access EGU

dune wavelength is being captured by the multiple single beam with the smaller sonar spacing, increasing to 30-100% with the larger spacing of 0-1.74-3.48-5.22 m (Fig. 4B). However, increasing beam spacing does not fully resolve discrepancies between repeat multibeam and multiple single beam bedload estimates (36.6% error; Fig. 4B), suggesting another factor is contributing to the observed discrepancies, most likely temporal resolution.

Using a linear interpolation we increase the temporal resolution of the data from 6 to 3 minutes. At this new sampling frequency, the original method yields a 2% error in March, but continues to overestimate bedload transport in July (67.5% error; Fig. 4C). Increasing the temporal resolution of the data results in more accurate estimates of lag. The cross-correlation method yields a 6.8% error in March and a 16.3% error in July (Fig. 4D), suggesting that the temporal resolution of the multiple single beam data will cause variation in cross-correlation-derived estimates of V_c.

4 Discussion

Bed elevation profiles recorded by repeat multi-, single- , and multiple single- beam sonar methodologies produce different estimates of bedload transport, but practical steps can be taken to reduce the mismatch.

Significant errors in fluxes computed can arise for two main reasons: (1) cross-correlation derived repeat multibeam bedform celerity estimates can show systematic bias, and (2) dunes can grow/shrink in response to unsteady flow conditions or varying sediment supply (Martin and Jerolmack, 2013; Rodrigues et al., 2015). Caution should be exercised when using cross-correlation to derive dune celerity, especially during higher transport stages and for relatively large time increments between successive measurements. It is good practice to check lags estimated using cross-correlation with manual measurements in order to compile a relationship that can be used to correct for systematic bias in estimated lag (Fig. 3A).

Using single beam bed elevation profiles, as dunes grow, transport is underestimated because period is overestimated. As dunes shrink, transport is overestimated because period is underestimated (Fig. 3B). It is therefore important to understand the time scales over which dunes size is responding to flow in order to assess the relative effect period distortion may be having on the bedload estimates. A sinusoidal growth model is proposed that accounts for geometric effects on bedload flux in unsteady flows, using measured dune heights and translations and a scaling relationship to predict dune wavelength from its height (Fig. 3C). Such a scaling relationship could be compiled over time for a specific single beam deployment and applied retroactively to entire time-series of bed elevation profiles. The sinusoid model could be applied in any operational setting where temporal variations in dune wavelength and a dune height-wavelength scaling relationship exist. A less generally applicable extension to this procedure could involve modeling the spatio-temporal evolution of the bed more explicitly using Fourier series (e.g. Guala et al., 2014).

In this study, accounting for temporal changes in dune geometry accounted for 28.9 (March) and 134.8 (July) tons/day in daily bedload rates computed using single beam, or 17.6% (March) and 28.3% compared to lag corrected repeat multibeam-derived rates.

Increasing the spatial resolution of the bed elevation data by using a multiple single beam system does not necessarily improve upon single beam transport estimates. Multiple single beam transport estimates do not suffer from distortions in

https://doi.org/10.5194/esurf-2019-38
Preprint. Discussion started: 19 August 2019

Earth Surface Dynamics Discussions Open Access EGU

period caused by changing dune wavelength but are sensitive to both beam spacing and sample frequency (Fig. 4). Ideally, sonar beams should be spaced such that a large proportion of the dune wavelength is sampled (Fig. 4B), although this is not always practical, especially in shallow water. If dune wavelengths change significantly according to flow, designing sampling to be optimal for a particular wavelength would not be recommended. A more effective approach to maximizing multiple single beam-derived bedload accuracy is to adjust sampling rate (Fig. 4C and D), calibrated in relation to a known range of dune migration rates. This is especially helpful for dune celerity estimates based on cross-correlation (Fig. 4A). We found the most accurate way to measure dune celerity from multiple single beam data is to measure time elapsed between successive dune crests.

5 Conclusions

In summary, repeat multibeam-derived elevation time-series are a more accurate means with which to estimate bedload than using single beam or multiple single beam, because the superior spatio-temporal coverage of these data allow for simultaneous resolution of V_c, H, and λ. However, there are significant practical advantages to using single beam or multiple single beam systems over repeat multibeam, and their capacity to monitor bedload over long periods may in some situations outweigh any disadvantages to do with greater errors in instantaneous bedload flux. We have offered a case study and practical guidelines to maximizing the efficacy of comparing bedload transport estimates derived from different sampling methodologies, which collectively will guide design of optimal bed sampling strategies for tracking dunes in rivers.

Code and data availability. Data and related codes are available at doi.org/10.5967/M02J6904.

Author contributions. Kate Leary designed the virtual experiments, developed code, and performed the simulations. Daniel Buscombe provided invaluable insight and helped with data analysis. Kate Leary prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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https://doi.org/10.5194/esurf-2019-38
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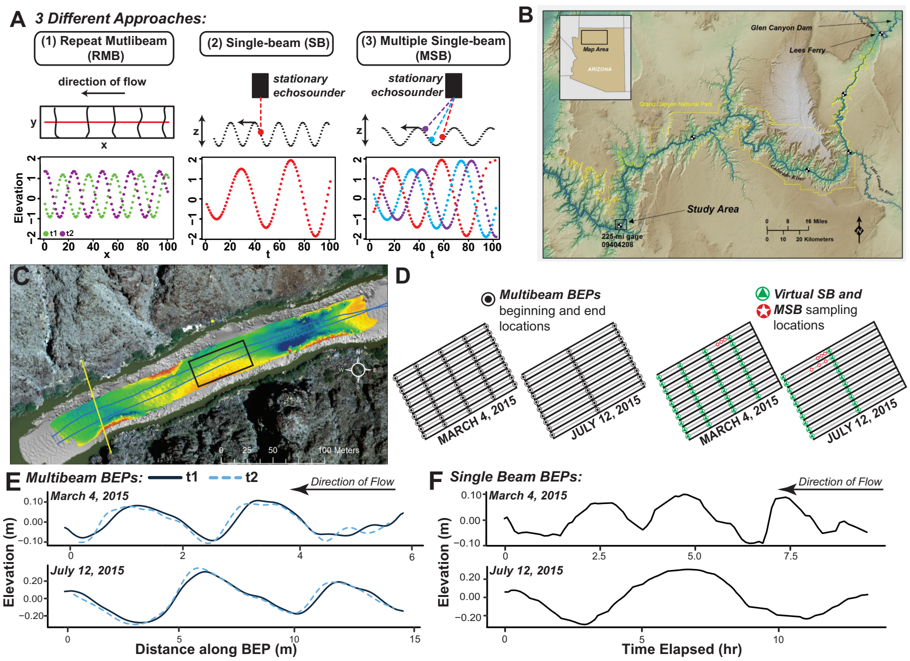

Figure 1. (A)Schematic of three common field methodologies for collecting bed elevation profiles (repeat multibeam, single beam, and multiple single beam) and the types of bed elevation profiles produced by each method. (B) Location of study area on the Colorado River in Grand Canyon National Park. Map adapted from Kaplinski et al. (2017) (C) Map of study reach. Yellow line indicates the location of the Diamond Creek USGS gage. Grey section indicates area mapped with single multibeam survey. Colored area indicates area over which repeat multibeam surveys were collected (colors indicate elevations where red is high and blue is low). The blue lines that bisect the repeat multibeam survey area indicate the track lines the boat drove along in order to obtain each survey. Black rectangle indicates area in which bed elevation profiles were extracted.(D) BEP extraction map for multibeam and virtual single- and multiple single- beam. Examples of repeat multibeam (E) and single-beam (F) bed elevation profiles for March and July data sets.

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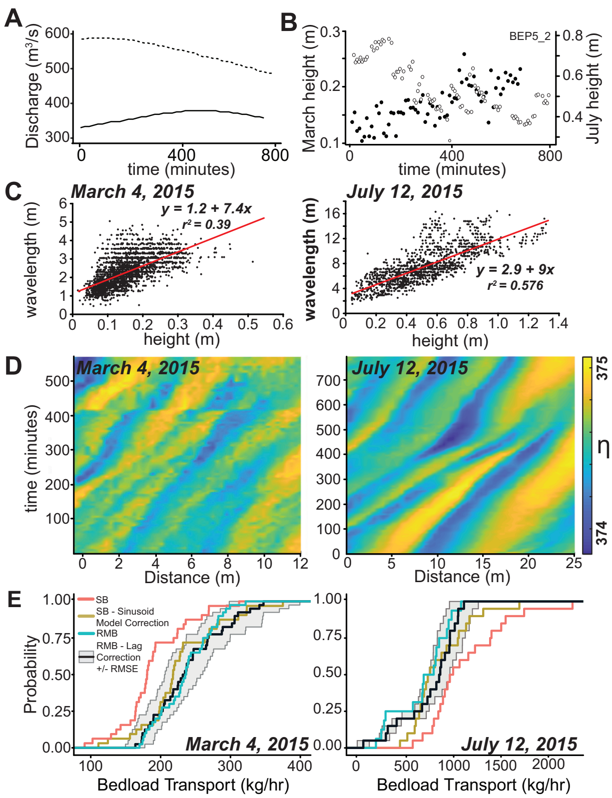

Figure 2. (A) Discharge during the sample time period. Dashed line is July data, solid line is March data. (B) Example of bed form height varying with time from BEP 5_2. Open circles indicate July data, closed circles indicate March data. (C) Height versus wavelength. Red line indicates linear regression of the data. (D) Cumulative density plots of single beam and repeat multibeam bedload transport estimates with added corrections for mischaracterized lag (repeat multibeam) and period (single beam).

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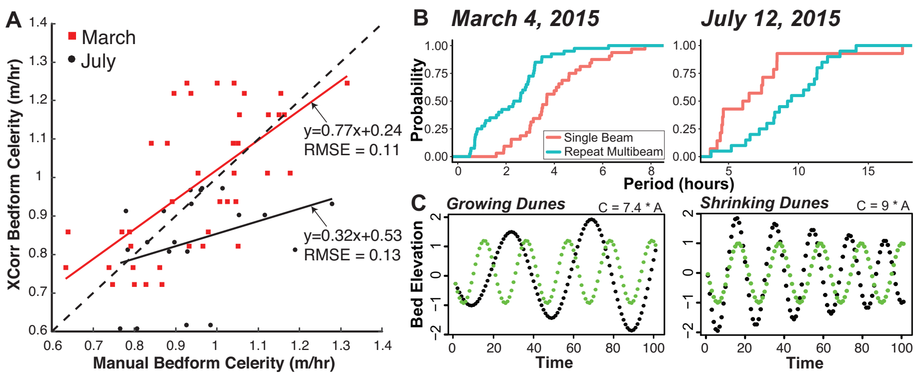

Figure 3. (A) Bedform celerity calculated using a manually picked lag versus a lag produce using a cross-correlation algorithm. The best fit linear regression of the data for each survey serves as a correction factor repeat multibeam celerity estiamtes. Dashed line represents x=y relation. (B) Cumulative density plots of period measured from single- and repeat multibeam BEPs. (C) Sinusoid model showing what the signle beam BEP would look like if dunes were growing/shrinking (black) or if dunes remained the same size through time (green).

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Preprint. Discussion started: 19 August 2019

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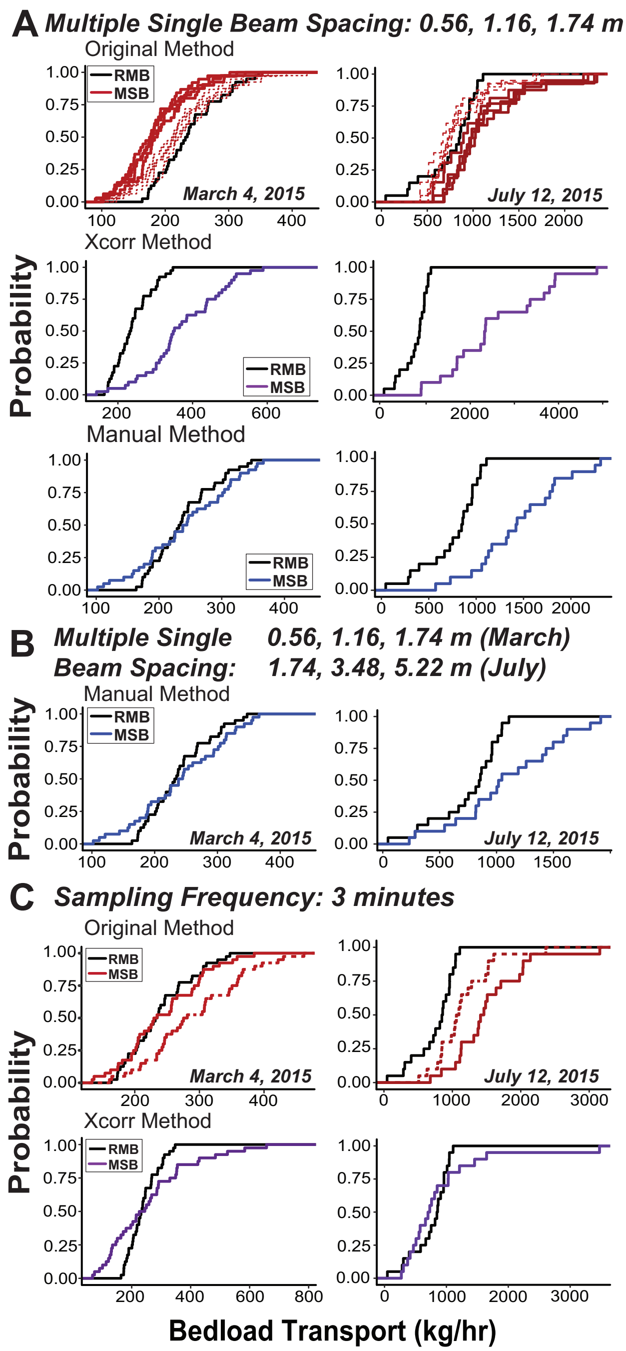

Figure 4. CDFs of lag-corrected repeat multibeam (black) and multiple single beam bedload transport estimates using the original (red), cross-correlation (purple), and manual methods (blue) to calculate bedform celerity for the MSB profiles. Dashed red lines are sine-corrected estimates.(A) Multiple single beam beam-spacing of 0 - 0.56 - 1.16 -1.74 meters for both March and July. (B) Multiple single beam beam-spacing of 0 - 1.74 - 3.48 - 5.22 meters for July. (C) Bedload transport estimates with 3 minute sampling frequency.