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Sampling suspended sand in rivers using instantaneous horizontal bottle samplers: a comparison against other techniques

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ABSTRACT: This study focuses on the efficiency of a horizontal sampling bottle (Van Dorn), a low-cost instantaneous water sampler for rivers. Sand concentrations from five experiments on the Colorado River are compared with isokinetic US P-61-A1 (point-integrating) and US D-96-A1 (depth-integrating) measurements. Instantaneous point sampling is more uncertain compared to point- or depth-integrating sampling owing to the lack of time or spatial averaging and the non-isokinetic sampling design of instantaneous horizontal bottle sampler. However, theoretical sand-concentration profiles can be fitted to instantaneous point sampling to improve the estimation of near-bed concentration.

1 INTRODUCTION

The understanding of sand dynamics in rivers is a matter for worldwide concern. The determination of suspended sediment discharge is required for river restoration and monitoring, river engineering and flood risk evaluation. The objective of suspended sediment sampling in rivers is to obtain a measurement that represents the average cross-sectional sediment concentration to get an accurate estimate of total flux through the cross-section. However, it remains very difficult to measure vertical and horizontal suspended-sand concentration gradients because existing methods are either time-consuming or incomplete.

Suspended sediment concentrations are typically measured by collecting samples of water-sediment mixtures in a river cross-section. Over the past century a large number of techniques and instruments have been developed for measuring or estimating the suspended sediment discharge in rivers. Mostly in the USA, considerable effort has been given to the evaluation of such techniques, including the development of a large range of isokinetic samplers and procedures, such as the depth-integrated method or point-integrated method (Gray and Landers, 2014).

There is a large range of samplers around the world, and some teams use also direct bottle sampling such as Van Dorn bottle to provide the samples in the cross section: Lupker et al. (2011) on the Ganga River (India), Jugaru Tiron et al. (2009) on the Danube River (Romania) or Armijos et al. (2016); Santini et al. (2019) on the Amazon River and tributaries (in Peru and Brazil).

To avoid bed material contamination in samples, sampling procedures do not collect water-sediment mixture in the near bed zone. A significant part of the sand load is carried below the lowest sampling point, it is therefore necessary to extrapolate the measured distributions toward the bed in order to determine the total sand load (Harrison, 1963). Point samples are useful for measuring the sediment concentration gradients to extrapolate sand concentration in the unmeasured zone. Moreover, greater accuracy can be obtained with point measurements (compared to depth-integrated measurements) because of larger sampling volumes for the determination of sediment concentration as well as particle grain size distribution of suspended sediment (Shah-Fairbank and Julien, 2015). However depth integrated measurements are faster than point

measurements, even for laboratory work. For depth integrated measurement on a vertical, the sample is made up of one bottle per vertical (or fewer when it's a verticals combined one) compared to the point integrated method which provides as many bottles as there are sample points.

Sediment samplers were often compared for validation; the main methodological problem, as for other measurement techniques, is the lack of reference. We never know the true sediment concentration value in the flow, especially in cases with various grain size particle distribution. Many samplers were compared in field conditions to improve the efficiency of the integration and point samples methods (FISP, 1944). Hicks and Duncan (1997) demonstrated that the depth-integrating sampler approach can induce an error in the mean velocity-weighted concentration of suspended sand compared with the point-sampler approach, due to the very short time to sample the high sand concentration zone. Long (1989) evaluated a $\pm 10\%$ relative standard error in measured concentration due to fluctuations. Filizola and Guyot (2004) found a 4 % difference between the 12 Liter horizontal bottle sampler for the Amazon River by comparison against a P-63 and a collapsible bag sampler (Meade, 1985). More recently Topping et al. (2011) identifies that depth-integrated sampling is subject to user-induced errors of the sampling protocol such as inadequate cross-section sampling and inadequate time averaging and he estimated the associated uncertainties. Gitto et al. (2017) suggest a 9 to 12 min sampling time to get a representative sample of the mean concentration value. All these comparisons on sampling procedures and devices can be done in various ways, but no method under field conditions can achieve perfect comparison due to temporal and spatial variation in sediment supply, particle size distribution, and streamflow velocity (Spicer, 2019).

The objective of this study is to evaluate the efficiency of the Van Dorn bottle sampler to describe a typical distribution of sand concentration and particle grain size within the cross section. A simple sampling method was used for the sand concentration measurement, using a Van Dorn deployed on three or more verticals and velocity measurement from an ADCP. Sand concentrations (particles $> 63 \mu\text{m}$) from five experiments on the Colorado River are compared with isokinetic US P-61-A1 on a single vertical (point integrating) and US D-96-A1 (depth-integrating) measurements on several verticals for the sand discharge computing.

2 EQUIPMENT AND METHODS

2.1 *Study site*

Flowing about 2330 km, the Colorado River is one of the most iconic river of the West of the USA. Since 1963, Glen Canyon Dam has regulated flows on the Colorado River and has greatly diminished the sediment supply in lowermost Glen Canyon and in Marble Canyon and Grand Canyon. Grain-size distribution of suspended sediment in regulated Colorado River below Glen Canyon Dam is broad and typically bimodal, with a silt and clay mode and a sand mode (Topping et al., 2007). The experiments of this study took place at 4 USGS gauging stations (cf. Figure 1).

2.2 *Van Dorn bottle sampler characteristics and deployment*

Van-Dorn or thief type water-sampling bottles are mostly used to collect instantaneous point water-sediment samples from lakes, reservoirs, estuaries. They also can be used to collect point samples from streams if the velocity is less than 0.5 m/s (Ward and Harr, 1990). They are lightweight and low-cost, and horizontal configuration is best for sampling at shallow depths. The one we used in this study is an acrylic 2.2 liter bottle with 2 kg extra weight. This sampler can be deployed by hand or with a reel. The measurement depth is read on a tag line and controlled with a depth sensor. When the bottle is at the desired depth the messenger is dropped down the line, so that it strikes the trip release pad. This releases the stoppers to seal the ends of the bottle and secures the sample inside. Van-Dorn water-sampling bottles are considered as non-isokinetic samplers because the sample enters the device at a velocity that differs from ambient stream velocity. The method for sampling in a river from a boat is to lower the point sampler while the engine is idle. To make sure of the verticality of the cable, the boat's drifted velocity must be higher than the sampler's. When the bottle is at the desired depth the messenger is dropped down the line, so that it strikes the trip release pad. This releases the stoppers to seal the ends of the bottle and

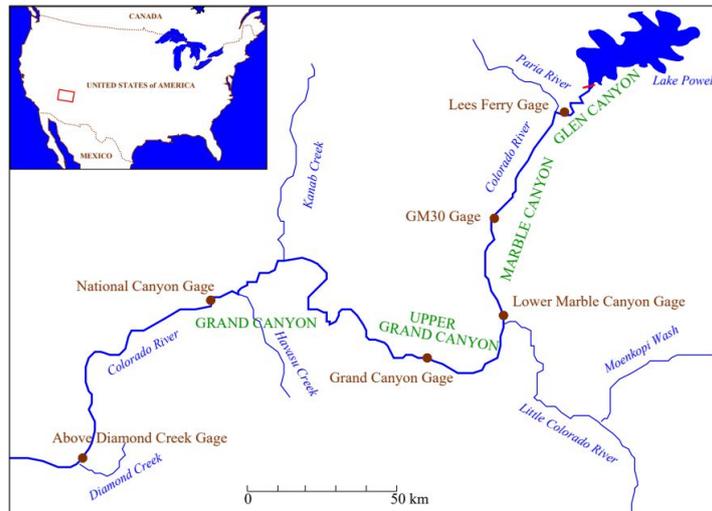


Figure 1. Study sites on the Colorado River (Camenen et al., 2019)

secure the sample inside. The boat is repositioned and this procedure is repeated until the whole cross section has been sampled.

2.3 Depth sampling accuracy with Van Dorn bottles

Depth measurement uncertainty is computed from a dataset with 96 comparisons between depth pressure sensor values and target depth readings on the tag line in various river configurations. This dataset is presented in Figure 2 a. Standard deviation for the difference between sensor data and operator readings is 0,46 m.

2.4 Comparison against isokinetic samplers on the Colorado River

Concentrations from five experiments on the Colorado River are compared with isokinetic US P-61-A1 (point integrating) and US D-96-A1 (depth-integrating) measurements. All the samples are analysed in concentration and particle grain size in the USGS GCMRC (Grand Canyon Research and Monitoring center) laboratory, according to US standards (ASTM D3977, 2007) (i.e. with a sand separation before analysis). Uncertainty with a 95 % confidence interval ($k=2$) is computed for each sample according to USGS uses (Gordon et al., 2000; Topping et al., 2010).

Two surveys took place at the Diamond Creek gauging station (Station 09404200) near Peach Spring. For the first survey (12/19/2019) six depths were successively sampled with the P-61-A1 sampler and the Van Dorn bottle. Then a full suspended sediment discharge measurement was achieved on one hand with the D-96-A1 and on the other hand by combining together ADCP velocity data and Van Dorn bottle samplings. During the second survey (04/01/2019) at Diamond Creek we compared again the Van Dorn bottle suspended sediment discharge with an integrated suspended sediment discharge. We also compared surface dip samples with point-integrated one. We focused on one detailed vertical sampling with both P-61-A1 and Van Dorn bottle, by sampling repetitions at the same measurement depth.

Three other suspended sediment discharge measurement surveys were done during a winter river trip in February 2019 on the Colorado river, first at RM30 (River Mile 30, station 09383050), second above Little Colorado River near Desert View RM61 (09383100), and near Grand Canyon at RM87 (09402500). At those stations we compared Van Dorn bottle samplings with an isokinetic DH-96-A1 sampler for sand discharge measurements.

2.5 Vertical sand concentration gradients modelling

Assuming a constant vertical diffusion parameter over the flow depth, mass conservation under steady-state conditions, we used an exponential relationship combined with measured sand concentrations to interpolate concentrations profiles in the water column at each vertical. This profile aims to describe vertical distribution of sediment concentration when downward settling

is balanced by upward. An exponential relationship was used to characterize the reduction in suspended-sand concentration with distance from the stream bed (Camenen and Larson, 2008):

$$C(z) = C_R \exp\left(\alpha \frac{z}{h}\right) \quad (1)$$

with z the distance from z_0 and h the vertical depth. C_R is a reference concentration and α a coefficient to be determined.

3 RESULTS AND DISCUSSION

3.1 Point measurement comparison between P-61 and Van Dorn bottle

The experiments at Diamond Creek were conducted to compare the concentrations from Van Dorn bottle and P-61 samplers. On December 19th, the centroid vertical was sampled at 6 different depths, all P 61-A1 samples were repeated three times, Van Dorn samples were single for each depth. Measurement time was almost the same (1 hour) between P-61-A1 exploration from the cable-car and Van Dorn bottle sampling from a boat. We observed a concentration gradient with both sampling techniques. Sand concentrations from Van Dorn sampler are in average 26% larger than the P-61-A1 (cf. Figure 2 b), however silt and clay concentration were in agreement between both samplers (-1% for the P61). Close to the stream bed concentrations and median grain size indicated for the Van Dorn bottle some coarsest particles compared to P-61-A1 samples (200 μm). Samples can be contaminated by sand clouds or bursts, like observed in sand bed rivers (Lapointe, 1992). It could illustrate the problem linked with instantaneous sampling and the temporal variability of the concentration. During this experiment water discharge was in a increase phase and this could also explain some differences, because the P-61-A1 samples were collected before the Van Dorn bottle one.

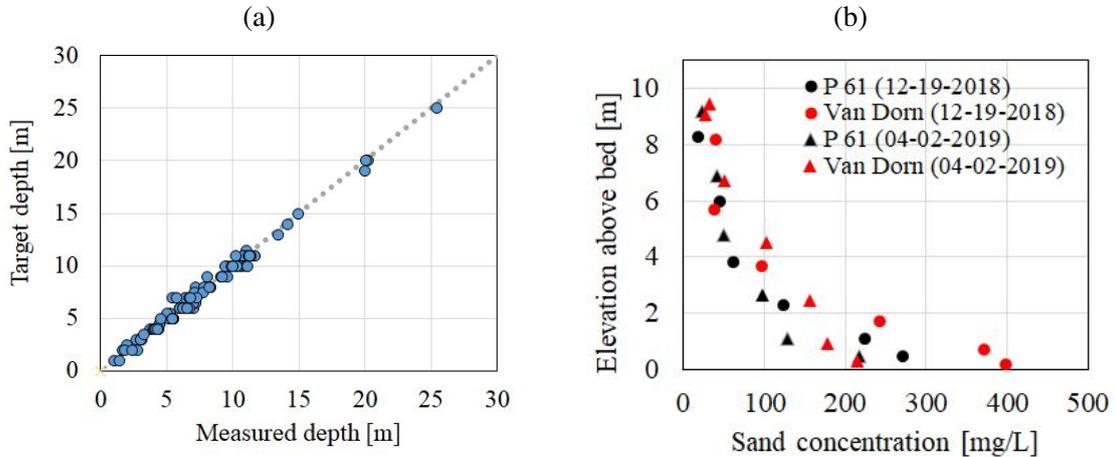


Figure 2. Depth sampling comparison between a pressure sensor and readings on the line by a field operator (a). Detailed vertical sand concentration profile at Diamond Creek, each concentration point is the average of three sample analysis (b).

After analyzing the results from this first comparison, we conducted a second experiment in April 2019. The same vertical was explored but alternatively, each P-61-A1 sample was followed with a Van Dorn bottle sample. Each sample was repeated three times and we observed, as expected, more scatter with the Van Dorn bottle samples than with the P-61-A1 which integrates concentration over time. The differences were quite the same between both sampling techniques (23 % higher concentration for Van Dorn) than compared to the first experiment (26 % higher). The median grain size for the Van Dorn bottle is also higher. During both surveys we observed median grain size particle gradients through the water column for the sand between 90 and 200 μm .

3.2 Modeling vertical gradients in suspended sand

We used a physically based method to extrapolate sand concentration in the unmeasured part of the vertical. Equation 1 was fitted to point-sample data at each vertical and can be applied to each sub-section around verticals to compute the suspended sand discharge. With this method, as showed with the example (cf. Figure 3 a) we could improve the estimation of the near-bed zone sand concentration.

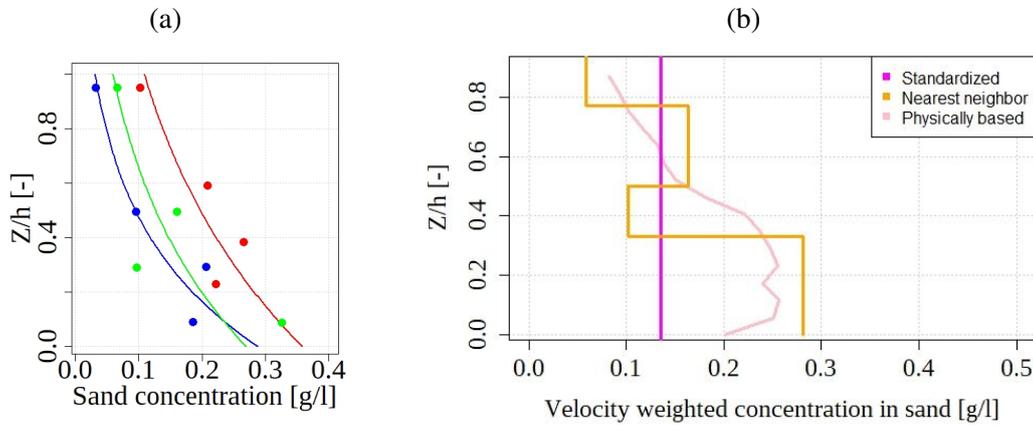


Figure 3. Exponential profile fitted on 3 verticals at Diamond Creek (04/01/2019) during suspended sand discharge measurement (a). One velocity weighted concentration vertical computed with 3 methods (b).

In the standardized method (ISO 4363, 2002) used to compute suspended sediment discharge, the near-bed zone is not considered different from the rest of the vertical. One mean concentration for the vertical is integrated from samples (point or depth integrated). Two other computation methods are applied on the dataset (cf. Figure 3 b). The velocity weighted concentration is the concentration times the corresponding velocity. Those methods are based on mobile ADCP data resolution. In the "nearest neighbour" method for each ADCP measured cell (velocity or discharge) we calculate the corresponding concentration, the nearest measured suspended-sand concentration is applied to each ADCP subsection. For the physically based method each concentration is computed from the fit on experimental data (cf. Figure 3 a) combined with ADCP velocities. These results indicate the importance of the near-bed zone and the way to compute the velocity weighted concentrations.

3.3 Velocity weighted concentration comparison

We can also compare velocity weighted concentrations on all the measured verticals. The DH-96-A1 sampler provides velocity weighted concentrations. For the point sample measurement we computed the velocity weighted concentration according to the standardized method by combining concentration with ADCP velocity data. Velocity weighted concentrations are compared for the five surveys on the Colorado river and computations show a 44 % average difference between DH-96-A1 and Van Dorn.

As shown in the Figure 4, velocity weighted concentrations are higher with the point sample method. Natural fluctuations of the sand concentration could explain this trend but there are other hypothesis: (1) Extrapolation method combine with ADCP data give a new estimation of suspended sand discharge in the near-bed zone with higher concentrations computed close to the stream bed. (2) Non-isokinetic samples yield higher concentrations.

4 CONCLUSION

In-situ comparisons of sampling strategies are affected by natural fluctuations in sediment concentrations, both spatially and temporally. The data collected with the different samplers were

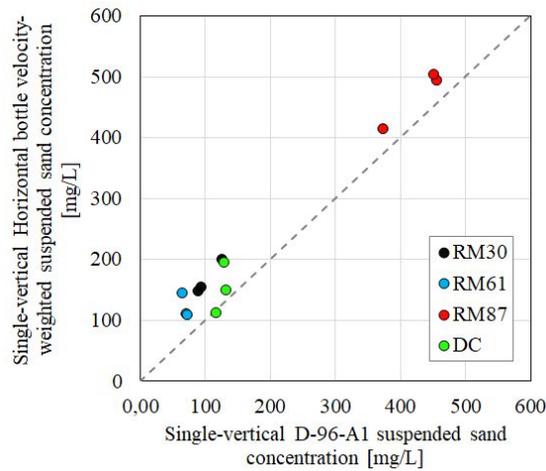


Figure 4. Single-vertical velocity-weighted sand concentrations from Van Dorn bottle compared to D-96-A1 sampler. Each point is one vertical comparison and each color belongs to the same cross section (with 3 different verticals).

acquired in rapid succession to minimize sediment supply variation. Depth-averaged, velocity-weighted suspended-sand concentration are compared for five surveys. Although the horizontal bottle samples compare well with the P-61-A1 samples for silt and clay concentration, the Van Dorn bottle sampler tends to collect higher sand concentrations (25 % more as an average) and coarser sand than does the P-61-A1 sampler. In terms of single-vertical computed concentrations (cf. Figure 4), the computations show a 44 % average difference between both approaches. This result could arise for two different reasons: (1) The Van Dorn bottle sampler could be sampling sand at a velocity lower than the ambient stream velocity owing to the shape of the sampler. This would cause the sand concentration and the sand grain size to be higher in the Van Dorn sampler than in the isokinetic sampler; (2) Turbulent fluctuations may cause instantaneous suspended-sand concentrations variations. If the higher concentrations are due to the non-isokinetic sampling it is difficult to improve except by changing the sampler. More samples can reduce the influence of the extremes in concentration and grain size from the turbulent fluctuations, but it is very expensive in terms of time in field and laboratory. Isokinetic time integrated samplers are more efficient to catch those variations with an optimal integration time.

Regardless of the source of the greater scatter in the Van Dorn samples, we can compute velocity weighted concentration by combining ADCP high resolution velocity data and concentrations from point samples. Van Dorn bottles are light, cheap and easy to deploy from a boat in various conditions for sediment discharge measurement. However, measurements are less accurate than isokinetic sampling but point sampling measurements provide a knowledge of sand gradients and allow a good computation of concentration in the unmeasured zone with a theoretical approach. Our results demonstrate that fitting theoretical sand-concentration profiles to point sample data with Van Dorn bottles, can reduce the uncertainty in depth-average concentrations to an acceptable level for sand flux determination, by taking into consideration the unmeasured zone near the stream bed.

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