Uniform grain-size distribution in the active layer of a shallow, gravel-bed, braided river (the Urumqi River, China) and implications for paleo-hydrology

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Abstract. The grain-size distribution of ancient alluvial systems is commonly determined from surface samples of vertically exposed sections of gravel deposits. This method relies on the hypothesis that the grain-size distribution obtained from a vertical cross-section is equivalent to that of the river bed. Such hypothesis implies first, that the sediments are uniform in size in the river bed, and second, that the sampling method implemented on a vertical section leads to a grain-size distribution equivalent to the bulk one. Here, we report a field test of this hypothesis on granulometric samples collected on an active, gravel-bed, braided stream: the Urumqi River in China. We compare data from volumetric samples of a trench excavated in an active thread and from surface counts performed on the trench vertical faces. Based on this data set, we show that the grain-size distributions obtained from all the samples are similar and that the deposit is uniform at the scale of the river active layer, a layer extending from the surface to a depth of approximately ten times the size of the largest clasts. As a consequence, the grid-by-number method implemented vertically leads to a grain-size distribution equivalent to the one obtained by a bulk volumetric sampling. This study thus brings support to the hypothesis that vertical surface counts provide an accurate characterization of the grain-size distribution of paleo-braided rivers.

1 Introduction

The size of the river-bed sediment and its spatial distribution result from transport and deposition mechanisms in alluvial systems. These mechanisms have been intensively studied to model fluvial behavior and landscape evolution (Wilcock and McArdell, 1993; Paola and Seal, 1995; Vericat et al., 2008; Piedra et al., 2012; Sun et al., 2015), and the temporal variations in grain-size distributions can be used to reconstruct paleo-environments or changes in tectonic and climatic conditions (Duller et al., 2010; Whittaker et al., 2011; Michael et al., 2014; Schlunegger and Norton, 2015; D'Arcy and Whittaker, 2016; Chen et al., Acc.). For this, the granulometry in ancient systems is often characterized on the basis of a single grain-size distribution sampled along vertical conglomeratic outcrops with a limited extension (Duller et al., 2010; Whittaker et al., 2011; Chen et al., Acc.). This simplification can be relevant to derive quantitative information about a stream from its deposits, but it is based on two assumptions. First, the sampled deposits must be equivalent to the ones that were in direct contact with the flow, and thus actively involved in the transport and deposition processes. Second, the grain-size distribution obtained from vertical outcrops must be equivalent to the reach-scale distribution (i.e. to the granulometry of the whole river bed).

In alluvial gravel systems, sediments can experience strong spatial variations in size. Downstream fining, which results from abrasion and preferential deposition of coarse particles, dominates the large-scale evolution of granulometry along a river path (Parker, 1991; Paola and Seal, 1995; Singer, 2008; Rice and Church, 2010). This preferential deposition of the coarse grains, together with the removal of fine grains by winnowing during low flows, can be responsible for the formation of a coarse layer, or armour, at the surface of the bed (Parker and Klingeman, 1982; Church et al., 1987; Wilcock and McArdell, 1993; Mao et al., 2011). This layer generally forms at reach scale (i.e. at the scale of the whole river bed, from several dozens to several hundreds of meters), although it is not always observed (Laronne et al., 1994; Laronne and Shlomi, 2007; Storz-Peretz and Laronne, 2013b, 2018). In addition, local (from a meter to a few tens of meters) trends in grain size are observed at the scale of the morpho-sedimentary elements (e.g., the bars, anabranches, and chutes for the braided rivers) that built the river bed with coarser or finer grained patches (Fig. 1)(Bluck, 1971; Smith, 1974; Milne, 1982; Lisle and Madej, 1992; Ashworth et al., 1992; Laronne et al., 1994; Laronne and Shlomi, 2007; Guerit et al., 2014; Storz-Peretz et al., 2016). As a consequence, two different features of granulometric sorting can occur at a given location along a stream: (1) a vertical evolution at reach scale with a surface layer (the first centimeters of the bed deposits, often scaled with the larger grains) coarser than what is below (the subsurface layer), and (2) local lateral variations associated with the morpho-sedimentary elements.

However, recent experimental findings suggest that the granulometry of gravel-bed braided streams might be uniform above a given scale. Indeed, over a hydrological season, grains actively involved in transport and deposition are contained within the active layer of a river bed. Using a physical model of braided streams, Leduc et al. (2015) show that this layer extends laterally over the whole river bed and that its thickness corresponds to the maximum difference in bed elevation measured in cross-section on the surveyed reach. They also observe that the active layer scales with the largest clast of the bed and extends over a thickness closed to 10 D_{90} (the 90^{th} percentile of the grain-size distribution). Based on the spatial organization of deposits with different calibers, a few experimental studies show that the sediments are well-mixed in the active layer, and thus suggest that the grain-size distribution of gravel-bed braided rivers is uniform at the scale of the active layer (Gardner and Ashmore, 2011; Leduc et al., 2015; Gardner et al., 2018) . However, such an analysis has not yet been performed on natural rivers. The first aim of this study is therefore to investigate the granulometric uniformity of this active layer of a gravel-bed braided river, which is a prerequisite for a relevant paleo-grain size sampling.

Two methods are commonly used to characterize the granulometry of gravel deposits (grains larger than 4 mm, Wentworth, 1922): the surface count (grid-by-number) and the volumetric (sieve-by-weight) methods. The first one consists in measuring the intermediate axis (b-axis) of the grains lying on the top of a river bed and located at the nodes of a predefined grid. It is classically used to determine the surface granulometry of present-day stream beds (Wolman, 1954; Church et al., 1987; Bunte and Abt, 2001). The second one consists in sieving a volume of sediments excavated from a river bed. It is generally used to sample the subsurface or bulk granulometry. The grain-size distribution obtained by this method is generally considered as representative of the whole river bed (Church et al., 1987; Bunte and Abt, 2001). The two methods lead to grain-size distributions that can be directly compared (Kellerhalls and Bray, 1971; Church et al., 1987; Bunte and Abt, 2001). In ancient alluvial systems, sediments are often cemented and it is not always possible to remove grains from outcrops. Photographic approaches, that do not require grain extraction, can be implemented for such outcrops but these methods suffer from the 2D exposure of 3D grains, which biases the measurement of their diameter (Kellerhalls and Bray, 1971; Church et al., 1987; Diplas and Fripp, 1992; Bunte and Abt, 2001; Storz-Peretz and Laronne, 2013a; Buscombe, 2013). Consequently, the surface count methodology adapted on vertical sections is preferably used (Duller et al., 2010; Whittaker et al., 2011; Michael et al., 2014; Chen et al., Acc.). However, this method has been developed to characterize the surface granulometry of active rivers where grains can be easily picked up and measured at the surface of the bed. To date, its validity on vertical sections has not been demonstrated. This is the second aim of this study.

Accordingly, we present a granulometric study on the Urumqi River, an active braided river in China. First, we describe the methodology implemented to sample the grain-size distributions by volumetric sieving and vertical surface counts. Then, based on a large data set, we show that despite local heterogeneities probably associated with the morpho-sedimentary elements of the river bed, the grain-size distribution of the sediments is uniform at the scale of the active layer. In addition, we observe that the distribution obtained by vertical surface counts is similar to the bulk granulometry of the river bed. This study thus shows that quantitative information about the granulometry of paleo-rivers can be accurately derived from surface counts along vertical conglomeratic outcrops.

2 Sampling site

The Urumqi River is a shallow (<1 m-deep), gravel-bed, braided river draining the northern side of the Tian Shan Range in China (Figs. 1 and 2a-b). This river initiates at the front of a glacier in the high range at 3600 m and runs northwards to the Junggar Basin where it dies out into the desert at an elevation of 1100 m. The sediments sampled in this study are located about 10 km downstream of the mountain topographic front. There, the Urumqi River braids within an alluvial valley cut into the deposits of a Pleistocene alluvial fan (Zhou et al., 2002; Guerit et al., 2016) (Fig. 2a-b). At this location, the catchment area of the river is close to 1000 km^2, its average slope is 0.02, and its runoff is mainly due to summer rains and snow or ice melt. As a consequence, the river mostly flows from May to September with a mean annual discharge of about 7.5 m^3 s^{-1} (Zhou et al., 1999) (Fig. 2b-c) and a total sediment load of 1-2 10^8 kg yr^{-1} (Liu et al., 2008, 2011). The river is almost dry outside of the high flow season and we can thus measure the granulometry of its bed (Fig. 1). The sediments found at the surface of the river bed are mostly gravels (Guerit et al., 2014).

To estimate the thickness of the active layer of the Urumqi River, we acquired 5 transverse topographic profiles across the river bed with a Timble S6 DR300+ total station with a point every meter on average. Differences in elevation between the highs and the lows of the river bed are in the order of 1 meter (Fig. 3). We thus estimate the active layer of the Urumqi River to be ∼1 meter. This morphological estimate is in good agreement with the one based on the D_{90} of the grain-size distribution at the same location. Indeed, the D_{90} is ∼ 10 cm at the sampling site (Guerit et al., 2014) and according to this value, the active layer should also extend from the surface down to 1 meter (i.e. 10 D_{90}) (Leduc et al., 2015).

3 Methodology

We combine two methods to characterize the grain-size distribution of the Urumqi River at the scale of its active layer: the volumetric and the surface count methods.

To characterize the surface-layer and subsurface granulometries of the river bed, we dig into its deposits a 7.2×1.2×1 m trench perpendicular to the flow direction of one thread (Fig. 4a-b). The sediments are excavated step by step from this trench as individual volumetric samples. We set the thickness of these samples to 2 D_{90} to insure that the largest grains are contained within one sample, and we determine the volume to be large enough to accurately characterize the grain-size distribution. Indeed, the accuracy of the volumetric method depends upon the sample weight with respect to the weight of its largest clast (Church et al., 1987; Haschenburger et al., 2007). Ideally, the largest grain of a volumetric sample should not contribute to more than 0.1% of the total weight but this criterion is difficult to achieve on the field and a relaxed criteria of 5% is acceptable when the large particules are $>$ 128 mm, as for the Urumqi River. In this study, each grain-size fraction is thus determined within ± 5%. The corresponding individual volumetric samples are 1.2×1.2×0.2 m, resulting in 30 samples labelled from 1 to 5 with respect to their depth, and from A to F with respect to their lateral position (Fig. 4b). We sieve the sediments using mesh sizes ranging from 63 μm up to 256 mm. Each mesh size is twice the previous one and we add three sieves (24, 48 and 96 mm) to obtain a more detail description in the gravel range. We then weigh the grains retained in each mesh to obtain a mass for a given diameter. The diameter of the grains retained in each sieve corresponds to the geometric mean of the sieve size and the following larger sieve, and it is considered to be the b-axis of the clasts (Church et al., 1987; Bunte and Abt, 2001; Guerit et al., 2014). To be consistent with the surface counts, for which only the grains larger than 4 mm are considered, we remove all the grains smaller than 4 mm (24% of the volumetric samples on average) from the analysis. These individual volumetric samples can be combined in different ways. (i) They can be used individually to characterize the grain-size distribution at local scale. (ii) They can be merged according to their depth (layers 1 to 5) or to their lateral position (columns A to F) to document potential granulometric variability associated with the location of a sample within the river bed. (iii) These individual volumetric samples can also be merged altogether to characterize the bulk granulometry of the Urumqi river bed at the scale of the active layer. (iv) Finally, they can be merged randomly and analyzed to document the granulometric evolution with respect to the weight of a sample.

In order to test whether the bulk granulometry of the river bed can be characterized from the sampling of a cross-section, we determine the grain-size distribution of the sediments outcropping on the walls of the trench by a vertical surface count. We implement the surface count methodology on the vertical sections of the river deposits (Fig. 4c-d), using a square grid of 20 cm (∼ 2 D_{90} in order to avoid sampling twice the same grain). We extract the grains located directly under each node and measure their b-axis (Wolman, 1954). However, grains smaller than 4 mm (19% of the total sample) are not considered in the analysis in order to reduce the measurement uncertainties (Kellerhalls and Bray, 1971; Church et al., 1987; Bunte and Abt, 2001). The resulting sample is thus composed of 298 grains with D > 4mm. We evaluate the confidence interval by a bootstrap method (Rice and Church, 1996; Bunte and Abt, 2001) for two characteristic diameters: the D_{50} (the diameter associated with the 50th percentile of the distribution) and the D_{90}. We estimate the D_{50} and the D_{90} of 10000 distributions built by randomly sampling with replacement 1 to 298 grains from the vertical surface sample. For both diameters, the range of values decreases with increasing bootstrap resample size. Above a given bootstrap sample size, values stabilize around the D_{50} (or D_{90}) of the initial sample and the confidence intervals correspond to the observed scatter.

Grain-size distributions often follow a lognormal distribution. We thus normalize our samples using the ϕ-scale ($\log_2$ based) and fit the distributions by a normal law. The simplest way to assess the accuracy of this fit is to compare the quantiles of our normalized samples to the quantiles of a normal distribution with the same mean and standard deviation (Q-Q plots) to test whether or not our samples follow such a distribution. For the volumetric samples, in order to avoid interpolation between the measurements, the quantiles correspond to those defined by the points issued from the discrete CDF, whereas for the vertical surface sample, we compare the Q_{10} to Q_{90} quantiles. If the distributions are similar, points align on the x = y line. Regardless of the nature of the grain-size distributions, the individual volumetric samples are not designed for statistical analysis as the volumetric method only provides the frequency distribution of the grain sizes. Accordingly, the similarities and differences between the 30 volumetric samples are discussed based on the visual comparison of the distributions together with the comparison of the characteristic diameters, D_{50} and D_{90}. However, ANOVA tests can be performed to compare the median values of the normalized distributions of the five layers (1 to 5) and of the six columns (A to F) issued from the trench. ANOVA tests determine whether at least two groups of samples come from the same population, based on the analysis of their variance. The ratio F of the variability within and between the different groups is calculated and compared to theoretical F-values. The tests are based on the null hypothesis that all the samples come from the same population of grains. This hypothesis is rejected if F is higher than the acceptable values F_{95} and F_{99} at a level of significance of 95% and 99%, respectively.

4 Results

4.1 Granulometry of the river bed at different spatial scales

4.1.1 Local variability in grain-size distribution

First, we analyze the grain-size distributions of the individual volumes excavated from the trench (Fig. 5a, Table 1). These 30 volumetric samples have an average weight of 440 kg and they are composed by more than 85% of pebbles (i.e. grains with $D \in$ 4-64 mm). The Q-Q plots indicate that all the normalized samples follow a normal distribution, although we observe some deviation for the coarser quantiles (inset Fig. 5a). In addition, the means and the standard deviations of the fitted curves are very similar (Fig. S1, Table S1). Accordingly, all the distributions show a similar shape and as they describe a similar range of values, the 30 curves plot close to each other (Fig. 5a). However, we observe some scatter between them and for any quantile, diameters can vary within a range of ±25-30% around the mean value. For example, the D_{50} vary between 17±1 mm and

32±2 mm for an average value of 23 mm, while their D_{90} are comprised between 52±3 and 126±6 mm for an average of 73 mm (Table 1).

4.1.2 Vertical sorting

Second, we merge the individual volumetric samples according to their depth (layers 1 to 5) and analyze the grain-size sorting with respect to depth (Fig. 5b, Table 2). On average, the different layers weigh 2600 kg and they are composed by 93% of pebbles. The five distributions are similar in shape and for any quantile, diameters vary within a limited range of ±10% around the mean value (Fig. 5b). This is illustrated by the limited variability of the characteristic diameters: their D_{50} range between 21±1 and 25±1 mm, while their D_{90} are comprised between 65±1 and 76±2 mm, for mean values of 23 and 70 mm, respectively (Table 2). The grain-size distributions of these larger samples is thus less scattered than the individual ones. In addition, we observe that the grain-size distribution of the surface layer (between 0 and 0.2 m, i.e. layer 1) is similar to the grain-size distribution of the subsurface layer (between 0.2 and 1 m, i.e. merged layers 2 to 5) (Fig. S2), and in particular, that the ratio between the D_{50} of the two layers is of 1.07. Moreover, the ANOVA tests confirm that the five layers are statistically indistinguishable (Table 3). Our data set thus indicates that at the scale of the active layer, there is no vertical sorting in the Urumqi river bed.

4.1.3 Horizontal sorting

Third, we merge the individual volumes according to their lateral position (columns A to F) and analyze the horizontal grain-size sorting (Fig. 5c, Table 4). On average, the different columns weigh 2200 kg and they are composed by 92% of pebbles. Here again, we observe that the samples exhibit a similar grain-size distribution and for all the quantiles, the scatter between these 6 samples is quite limited (Fig. 5c). For example, the D_{50} range between 21±1 and 26±1 mm, while their D_{90} vary between 64±1 and 76±2 mm (Table 4). This corresponds to a range of ±13% and ±10% around the means of the samples (23 and 71 mm, respectively). Here again, the ANOVA tests confirm that the six columns are indistinguishable in terms of grain size (Table 3). Thus, at the scale of the active layer, the Urumqi river bed has no horizontal granulometric sorting. In consequence, grain-size distributions issued from vertical pits are equivalent to distributions issued from horizontal layers.

4.2 Granulometry of the river bed according to sampling methods

Finally, we merge all the volumetric samples together to determine the bulk granulometry of the river bed (Fig. 5d, Table 5). Based on 13150 kg of sediments, this large volumetric distribution is composed of 92% of pebbles, and the Q-Q plot indicates that the normalized sample also follows a normal distribution (inset Fig. 5d). It is characterized by a D_{50} of 23±1 mm and a D_{90} of 73±1 (Fig. 5d, Table 5).

We compare this distribution to the one obtained by vertical counts along the walls of the trench (Fig. 5d). Based on 298 grains ($D \geq 4$ mm), this sample is made up of 85% of pebbles. From the bootstrap approach, we find the D_{50} and D_{90} to be respectively defined within a range of ±15% and ±20% (Fig. 6), and here again, the Q-Q plot indicates that the normalized sample follows a normal distribution (inset Fig. 5d). The median diameter D_{50} of this vertical surface count is 20±4 mm, while its D_{90} is 82±16 mm (Table 5). Accordingly, the shape of the vertical surface grain-size distribution compares well with the bulk volumetric distribution of the trench, but also with the 30 individual volumetric samples as well as with the 5 layers and the 6 columns (Fig. 5). Except for the smallest grain sizes, the diameters associated to each quantile are very similar (Fig. 5). A Q-Q plot also confirms that the distribution obtained by the vertical surface count is similar to the bulk volumetric one (Fig. S3). This comparison indicates that the characterization in cross-section of the Urumqi active layer is equivalent to the more traditional volumetric method, and thus shows for the first time that surface counts implemented on vertical outcrops can be used as proxies for a bulk volumetric sampling.

5 Discussion

5.1 Grain-size uniformity in an active, gravel-bed, braided river

At local scale (< meter to 10s of meters), features of grain-size sorting are commonly observed and documented on the bed of braided gravel-bed streams (Leopold et al., 1964; Bluck, 1971, 1976; Smith, 1974; Ashworth, 1996; Ashmore, 2013; Guerit et al., 2014). In these rivers, this surface sorting is associated with the morpho-sedimentary elements (bars, anabranches and chutes) that shape the river bed. In the Urumqi River, we also observe local variations in grain sizes in the vertical section of the active layer with small areas enriched in fine or coarse grains (Fig. S4) and this variability could be the expression in cross-section of the small-scale sorting associated with the morpho-sedimentary elements observed on the bed (Guerit et al., 2014). We propose that this sorting may be responsible for the scatter observed between the granulometric distributions of the 30 individual volumetric samples (Fig. 5a), as they scale in size with the morpho-sedimentary elements corresponding to meters-large and centimeters-to-decimeters-deep grain-size patches. This suggestion is supported by the fact that scatter around the mean values seems to be dependent on the sample size (Fig. 5).

To assess the minimum weight required for a sample to go over the local variability and to be equivalent to the bulk one, we randomly merge without replacement the individual volumetric samples to obtain 600 composite volumetric samples of 241 to 13150 kg. We then determine the D_{50} and D_{90} as a function of the sample weight (Fig. 7). Variability around the mean decreases with increasing weight and at first order, the sample weight must increase by a factor 2 for the variability around the mean value to decrease by 5% (Fig. 7). We observe that ∼5000 kg of sediments larger than 4 mm (about 11 individual volumetric samples) are required to estimate a D_{50} and a D_{90} within a range of ±10% around the mean values (Fig. 7). To reach a level of accuracy equivalent to the bulk sample (±5%), we observe that 9000 kg (about 20 individual volumetric samples) are necessary (Fig. 7). This analysis confirms that small-scale grain-size sorting exists in the active layer of the Urumqi River, but this sorting becomes negligible as the sample size increases. The active layer of the Urumqi River thus appears as the superposition of small-scale structures (the morpho-sedimentary elements), whose variability vanishes above a given scale. Accordingly, at the scale of the active layer, the grain-size distribution of the Urumqi River deposits can be considered as uniform.

The uniformity in the grain-size distributions of the various samples we analyze (individual volumes, layer and column samples), and their similarity with the bulk one, indicates that the Urumqi river bed is not armoured at reach scale. In consequence, at any depth or location of the active layer of the bed, the deposits are representative of the sediments transported as bedload in direct contact with the flow, providing that the sample is large enough to integrate at least a dozen of morpho-sedimentary elements. Our results therefore accord with the experimental findings of Gardner and Ashmore (2011), Leduc et al. (2015) and Gardner et al. (2018). The agreement between field and physical experiments leads us to propose that the absence of vertical and lateral sorting may be typical of non-armoured, gravel-bed, braided rivers.

5.2 Grain-size sampling in ancient systems

We show that the broadly used Wolman grid-by-number method can be implemented on vertical sections to characterize grain-size distributions with a good level of confidence. In addition, the granulometric uniformity at the scale of the Urumqi active layer implies that the grain-size distribution of paleo-rivers can be adequately determined from conglomeratic outcrops. Our study thus legitimates this kind of sampling (Duller et al., 2010; Whittaker et al., 2011; Michael et al., 2014; Chen et al., Acc.), at least for unarmoured braided rivers, for stratigraphical or paleo-hydrological reconstructions .

However, three limitations must be considered to generalize our results to any field work in ancient systems. First, this study is based on grains removed from trench walls so that it is possible to measure their actual b-axis. In ancient systems, deposits are often cemented and it is not always possible to remove grains from outcrops. In that case, outcropping diameters should be identified before implementing measurements. Indeed, in a section perpendicular to the main flow, the b- (intermediate) and c- (small) axis are expected to be visible. In such situation, the b-axis will appear to be the longest one. On the contrary, in a section parallel to the main flow, the a- (long) and b- (intermediate) axis are expected to be visible, and the b-axis will then appear to be the shortest one (e.g., Bunte and Abt, 2001). Indications of paleo-flows can thus help to identify the actual b-axis.

Second, the grain-size distribution of the deposits can be altered after deposition or after surface abandonment by several factors. Aeolian processes can either bring fine material that can infiltrate the gravels and decrease the global granulometry of the deposits, or lead to the formation of desert pavements (McFadden et al., 1987, 1998). Soils development on the top of a surface can also induce the formation of secondary particules that will contaminate the initial gravel deposits (e.g., Pimentel, 2002). However, the gravel fraction should not be affected by such secondary processes that generally affect the fine-grain content, and truncation of the grain-size distribution below a given diameter (4 mm here) should insure the removal of these secondary signals. Moreover, as these processes might mostly affect the upper part of gravel deposits (Wooster et al., 2008; Cui et al., 2008), samples should be acquired as much as possible where evidences for such modifications are not observed. With time, chemical alteration can also modify the size of the initial gravels, but this process might be difficult to quantify. Accordingly, we suggest that outcrops showing evidences of gravel alteration should not be sampled.

Finally, the third limitation is related to the limited thickness of the active layer, which extends in depth over several D_{90} only for an active system (Laronne et al., 1994; Gardner and Ashmore, 2011; Leduc et al., 2015). Moreover, the thickness of this layer is not fixed though time as it could evolve with potential changes of the river characteristics. The sediments deposited during an hydrological season can also be remobilized afterwards if the river incises, leading to a partial or total destruction of the former active layer(s). In stratigraphic successions, deposits are stacked vertically through time and consequently, to compensate for this limited extension in depth of the active layer and for its potential preservation changes through time, the grids used for vertical surface counts should extend laterally rather than vertically to stay as much as possible within the same sedimentary layer.

6 Conclusions

We perform a granulometric study on the deposits of the Urumqi River, an active, gravel-bed, braided stream in China. Based on a large data set collected by volumetric and vertical surface count samplings, we show that the grain-size distribution of the river bed is uniform at the scale of its active layer. Despite some local variabilities related to small-scale grain-size features, there is no vertical or lateral granulometric trend within this layer. Because our findings confirm earlier physical models (Gardner and Ashmore, 2011; Leduc et al., 2015; Gardner et al., 2018), we propose that, beyond the Urumqi River, this uniformity be the case for all the non-armoured, gravel-bed, braided streams.

This uniformity implies that it is possible to determine the grain-size distribution of gravel-bed braided alluvial systems from vertical outcrops. We show that the grid-by-number method, initially developed and tested on the horizontal surface of river beds, can be implemented on vertical outcrops to obtain samples equivalent to a volumetric investigation in non-armoured, gravel-bed rivers. This study thus supports the hypothesis that vertical surface counts can be implemented on conglomeratic outcrops to provide an accurate characterization of the grain-size distribution of paleo-braided rivers.

Competing interests. The authors declare no competing interests.

Acknowledgements. We are thankful to two anonymous reviewers and to the associated editor for their comments that strongly improved the quality of the paper. The study presented in this manuscript was conducted with research grants from the CNRS-INSU RELIEF program and the French-Chinese CNRS-CAS International Associated Laboratory SALADYN, as well as from the IPGP BQR and Potamology programs. L.G. benefitted from a PhD grant from the French Ministry of Research and Higher Education (MESR). This work is partially supported by the National Natural Science Foundation of China (No. 41471001).

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Figure 1. Example of a shallow gravel-bed braided river bed during the dry season (Urumqi River, China). Spatial variations in grain size can be observed at the surface of the river bed with finer- and coarser-grained areas.

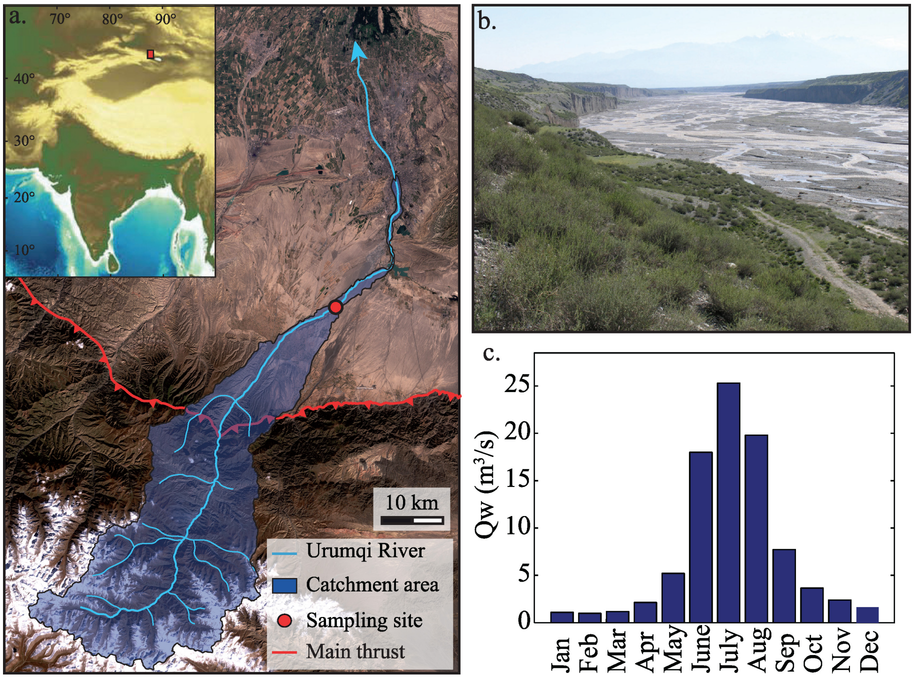

Figure 2. a) Location, drainage network and catchment area of the Urumqi River system, b) picture of the river at the sampling site during the high flow season, and c) annual hydrograph of the river (after Zhou et al., 1999).

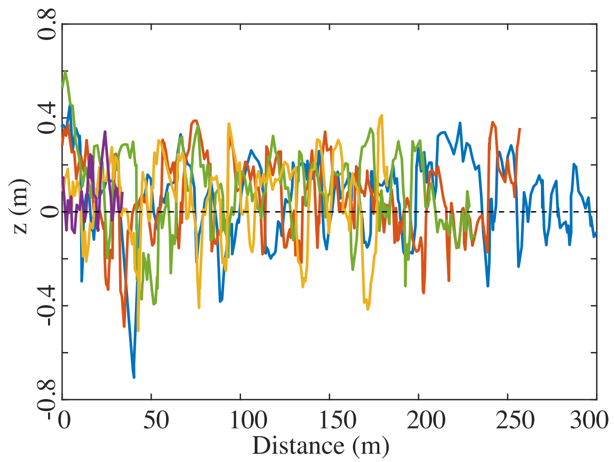

Figure 3. Transverse topographic profiles acquired along the Urumqi River bed. Elevation is given as the deviation from the mean bed elevation at each cross section.

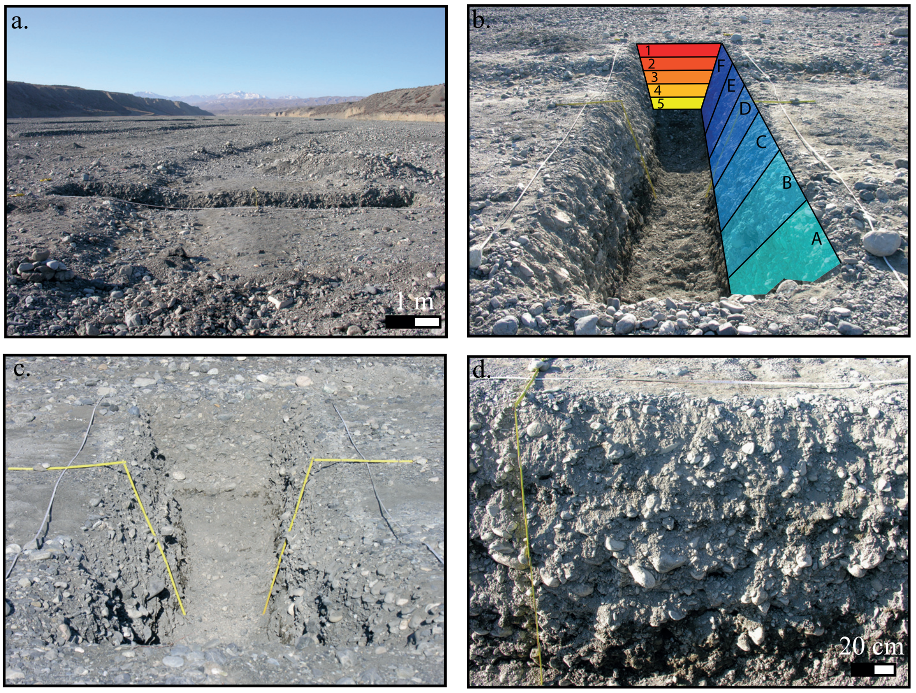

Figure 4. View a) from the north and b) from the west of the 7.2-m long and 1.2-m large trench. On this second view, the sampling nomenclature is indicated. Layers are colored from red to yellow and labelled from 1 to 5, whereas columns are colored from light to dark blue and labelled from A to F. c) and d) Implementation of the vertical surface counts along the trench walls with a node every 20 cm.

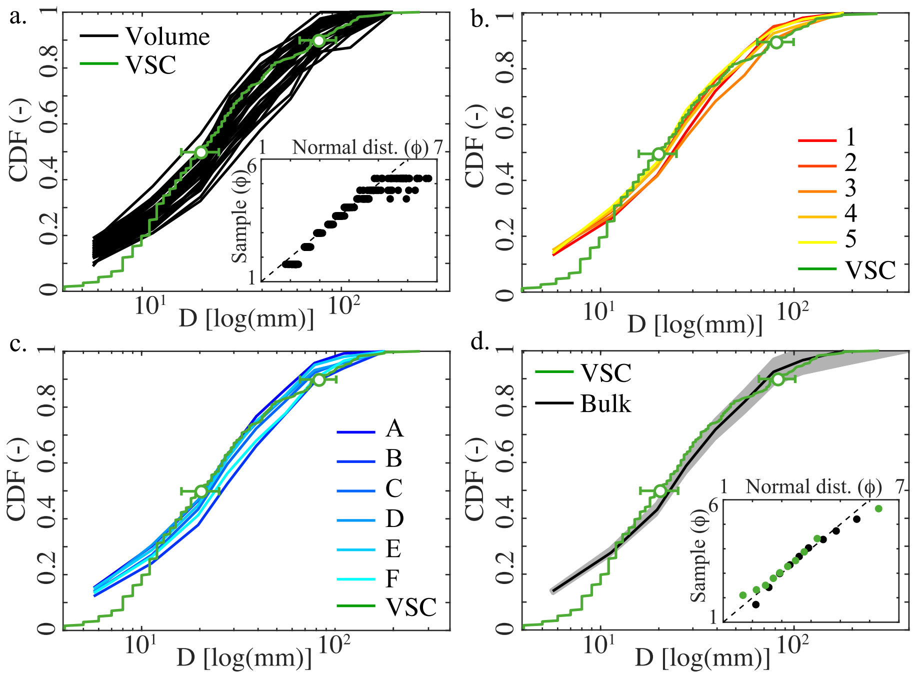

Figure 5. Grain-size distributions of a) the 30 individual volumetric samples excavated from the trench (1.2×1.2×0.2 m, black lines) with corresponding Q-Q plots in inset (ϕ-scale), b) the five 20 cm-thick layers of the trench from the surface to 1 m-deep (red to yellow), and c) the six 1.2 m-wide columns of the trench from the west to the east (dark to light blue). On each figure, the grain-size distribution sampled by vertical surface counts on the trench wall is indicated (VSC, green), together with its D_{50} and D_{90} and their associated uncertainties (green dots). d) Grain-size distributions of the two bulk samples obtained by vertical surface counts on the walls of the trench and volumetric sieving of the trench (bulk, black) with corresponding Q-Q plots in inset (ϕ-scale). The gray shape corresponds to the uncertainties of the volumetric sample quantiles. These four graphs suggest that the sediments of the Urumqi River active layer follow a similar distribution and are thus uniform at the scale of this active layer in terms of grain-size distribution.

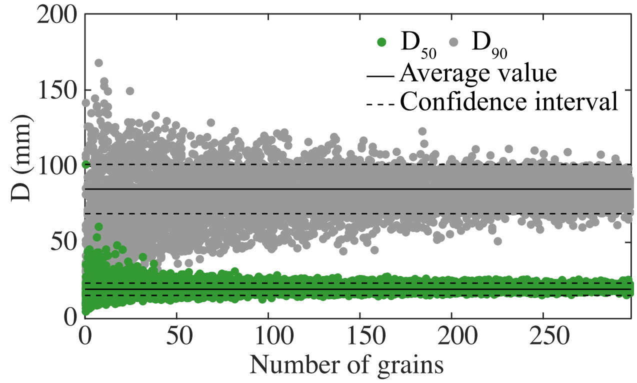

Figure 6. Estimation of the confidence interval by a bootstrap approach of the D_{50} (green dots) and D_{90} (gray dots) of the surface counts performed along the walls of the trench (see text for details on the method). Diameters are defined within a range of ±15-20%.

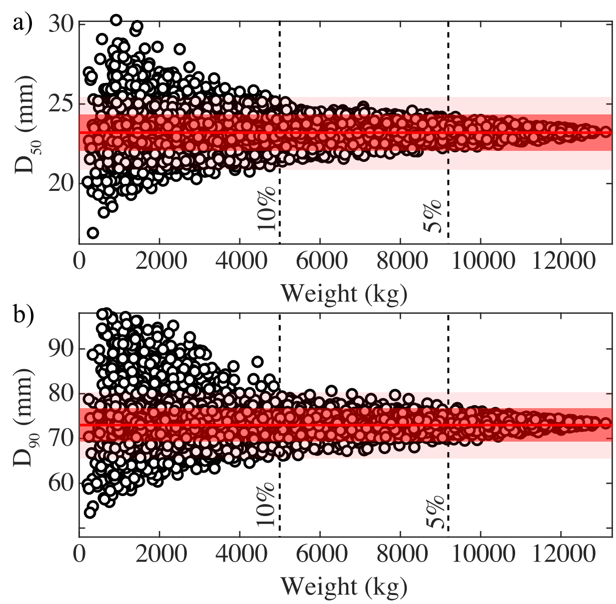

Figure 7. Evolution of a) the D_{50} and b) the D_{90} with respect to the sample weight. These diameters are issued from grain-size distributions built by random merging without replacement of the individual volumetric samples. Red line is for the mean value, the dark red area for the mean±5%, the light red area for the mean±10%. The black dashed lines indicate the visually-estimated threshold for a sample to be within ±10 and 5 %.

Table 1. Main characteristics of the local-scale samples excavated from the trench. P and C are the proportions of pebbles and cobbles within the sediments defined after Wentworth (1922). D_{50} is the mean diameter and D_{90} the 90^{th} quantile of the grain-size distributions. Confidence intervals are calculated from the Church et al. (1987)'s criteria.

Sample	Size	P (%)	C (%)	D_{50} (mm)	D_{90} (mm)	Sample	Size	P (%)	C (%)	D_{50} (mm)	D_{90} (mm)
A1	649 kg	96	4	23 ± 1	66 ± 3	D1	372 kg	97	3	17 ± 1	52 ± 3
A2	300 kg	100	0	21 ± 1	56 ± 3	D2	309 kg	92	8	22 ± 1	74 ± 4
A3	506 kg	96	4	20 ± 1	62 ± 3	D3	273 kg	95	5	23 ± 1	70 ± 4
A4	475 kg	93	7	20 ± 1	70 ± 4	D4	314 kg	86	14	26 ± 1	126 ± 6
A5	338 kg	89	11	22 ± 1	66 ± 3	D5	241 kg	97	3	20 ± 1	60 ± 3
B1	607 kg	85	15	32 ± 2	97 ± 5	E1	618 kg	97	3	25 ± 1	65 ± 3
B2	615 kg	95	5	24 ± 1	65 ± 3	E2	465 kg	97	3	21 ± 1	60 ± 3
B3	599 kg	88	12	29 ± 1	94 ± 5	E3	504 kg	88	12	25 ± 1	78 ± 4
B4	510 kg	88	12	22 ± 1	74 ± 4	E4	441 kg	97	3	21 ± 1	64 ± 3
B5	343 kg	83	17	27 ± 1	104 ± 5	E5	484 kg	96	4	20 ± 1	60 ± 3
C1	363 kg	97	3	20 ± 1	61 ± 3	F1	537 kg	88	12	24 ± 1	88 ± 4
C2	368 kg	88	12	24 ± 1	78 ± 4	F2	554 kg	91	9	27 ± 1	77 ± 4
C3	271 kg	90	10	27 ± 1	77 ± 4	F3	399 kg	91	9	23 ± 1	70 ± 4
C4	386 kg	90	10	25 ± 1	76 ± 4	F4	525 kg	87	13	25 ± 1	89 ± 4
C5	271 kg	98	2	20 ± 1	60 ± 3	F5	509 kg	91	9	23 ± 1	73 ± 4

Table 2. Main characteristics of the five layers issued from the trench. P and C are the proportions of pebbles and cobbles within the sediments defined after Wentworth (1922). D_{50} is the mean diameter and D_{90} the 90^{th} quantile of the grain-size distributions. Confidence intervals are calculated from the Church et al. (1987)'s criteria.

Sample	Size	P (%)	C (%)	D_{50} (mm)	D_{90} (mm)
Layer 1	3226 kg	95	5	24 ± 1	69 ± 3
Layer 2	2523 kg	95	5	22 ± 1	65 ± 3
Layer 3	2657 kg	91	9	25 ± 1	76 ± 4
Layer 4	2566 kg	92	8	22 ± 1	72 ± 4
Layer 5	2161 kg	93	7	21 ± 1	66 ± 3
Average	2626 kg	93	7	23 ± 1	70 ± 4

Table 3. ANOVA tests on the grain-size distributions of the five layers and the six columns from the trench. df is the number of degrees of freedom, SS the sum of square, and MS the mean square. The null hypothesis is that there is no difference in the mean values of the grain-size distributions, and P is the probability to get the obtained F value from samples extracted from a single population. The five layers, as well as the six columns, are indistinguishable (F< F_{95})

Group	Variation source	df	SS	MS
	Inter	4	0.03	0.01
	Intra	25	0.50	0.02
Layers 1 – 5	Total	29	0.53	0.02
	F	F_{95}	F_{99}	P
	0.42	2.76	4.18	0.80
	Inter	5	0.18	0.04
	Intra	24	0.35	0.01
Columns A – F	Total	29	0.53	0.02
	F	F_{95}	F_{99}	P
	2.39	2.62	3.90	0.07

Table 4. Main characteristics of the six columns issued from the trench. P and C are the proportions of pebbles and cobbles within the sediments defined after Wentworth (1922). D_{50} is the mean diameter and D_{90} the 90^{th} quantile of the grain-size distributions. Confidence intervals are calculated from the Church et al. (1987)'s criteria.

Sample	Size	P (%)	C (%)	D_{50} (mm)	D_{90} (mm)
Column A	2268 kg	95	5	21 ± 1	64 ± 3
Column B	2674 kg	88	12	26 ± 1	77 ± 4
Column C	1659 kg	92	8	23 ± 1	73 ± 4
Column D	1509 kg	93	7	21 ± 1	71 ± 4
Column E	2512 kg	95	5	22 ± 1	67 ± 3
Column F	2524 kg	90	10	24 ± 1	76 ± 4
Average	2191 kg	92	8	23 ± 1	71 ± 4

Table 5. Main characteristics of the large-scale samples. P and C are the proportions of pebbles and cobbles within the sediments defined after Wentworth (1922). D_{50} is the mean diameter and D_{90} the 90^{th} quantile of the grain-size distributions. Confidence intervals are calculated by bootstrapping for the surface counts and from the Church et al. (1987)'s criteria for the volumetric sample.

Sample	Size	P (%)	C (%)	D_{50} (mm)	D_{90} (mm)
Total volume	13150 kg	92	8	23 ± 1	73 ± 4
Vertical surface count	298 grains	85	15	20 ± 4	82 ± 16