Comment on "Photographic techniques for characterizing streambed particle sizes"

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Whitman et al. (2003) presented an interesting photographic technique for measuring river-bed sediment size and embeddedness. The sizing technique is based on photographing a patch of sediment, scanning the image, manually digitizing the grain boundaries and using computer-based image analysis to measure the resulting objects (grains). As they point out, sedimentologists and geomorphologists have used such approaches for almost 20 years (Ibbeken and Schleyer 1986), building on earlier techniques utilizing manual measurements in photographs (Adams 1979). Indeed, there is increasing interest in fully automated methods of grain-size measurement using images collected with a digital camera, removing the need to either scan the photograph or manually digitize individual grain boundaries (Butler et al. 2001; Reid et al. 2001; Sime and Ferguson 2003; Graham et al. 2005a, b). The use of a photographic approach is particularly appropriate for fisheries and monitoring applications because, unlike conventional measurement techniques, it is non-invasive, preserving the substrate that is being studied.

Whitman et al. (2003) found a significant difference between the grain-size distributions and mean particle sizes determined by their photographic technique and Wolman sampling at five sites (as determined by Kolmogorov-Smirnov and *t*-tests). These results are confirmed by their Figure 3a, which shows a clear difference between the grain-size distributions obtained by the two techniques for a single site. They concluded that these differences may result from an error in one of the techniques, but were unable to fully account for them or determine which of the techniques gave the most reliable results. In fact the disparity is, at least partly, accounted for by reanalyzing their data in light of two principles of grain-size sampling that Whitman et al. (2003) overlooked. This re-analysis illuminates their comparison and, along with a suite of results from the sedimentological literature, suggests that Wolman and photographic sampling can be of comparable quality. This is important because photographic sampling has several key advantages over manual Wolman sampling, not least its non-invasive nature and cost-saving implications.

First, the minimum grain size included in the grain-size distributions was different for the two techniques. The photographic samples were deliberately truncated at 2 mm. In contrast, all of the grains recorded in the Wolman samples are larger than 8 mm (their Figure 3a). It is therefore unsurprising that the grain-size distributions and mean particle sizes, reported by Whitman et al. (2003), are different.

Whitman et al. (2003) may have retained different lower size limits in their analysis to highlight the bias against fine material that is inherent in Wolman sampling (Fripp and Diplas 1993). This bias arises because small particles are difficult for operators to reach and manipulate under water, particularly when the particles sit in interstices between larger pebbles (Marcus et al. 1995; Rice 1995; Bunte and Abt 2001). Whether the 8 mm limit reflects deliberate truncation (as is the conventional means of mitigating this bias) or is simply an excellent practical illustration of it, the comparison with the photographically derived results makes the point that conventional Wolman sampling may not be appropriate for fisheries applications where fine sediments are a key concern; for example when assessing gravel spawning quality (Bjornn and Reiser 1991). However, this does not provide a fair means of comparing the performance of Wolman sampling with the photographic technique; a comparison that needs to be made precisely because a photographic technique capable of accurately sampling finer grains would be very valuable.

For this, a common truncation point must be used. This could have been achieved by truncating the photographic samples at 8 mm, or by including a count of the number of points in the Wolman sample where grains smaller than 8 mm were observed and attributing these to a nominal intermediate size (e.g. 4 mm). Because of the difficulty of undertaking a Wolman sample underwater (Marcus et al. 1995; Rice 1995; Bunte and Abt 2001), the former approach is probably most reliable if the requirements of the study are met by such a method.

Second, the grain-size distributions produced by different sampling and measurement techniques are not directly comparable (Kellerhals and Bray 1971; Diplas and Sutherland 1988; Fraccarollo and Marion 1995). Sampling strategies may be based on sampling a predefined number of grains on a grid, sampling the grains within a predefined area, or sampling the grains contained within a predefined volume. Grid or areal methods are limited to sampling the surface sediment and volumetric methods are used for the subsurface. Furthermore, the grain-size distributions may be based on either the weight of the grains or a count of the number of grains. Combining these options, there are six possible ways of sampling and recording grain size, each of which will produce a different apparent grain-size distribution for the same sediment.

Of interest here is the relation between the grain-size distributions produced by Wolman and photographic sampling strategies, both based on grain counts, for the surface layer of sediment. A Wolman sample is a grid-based sample, in which the probability of selecting a grain of a given size is proportional to its area. So, a grain of area A is twice as likely to be selected as a grain of area $A/2$, all else being equal. In contrast, a photographic sample – when analyzed using the method employed by Whitman et al. (2003) – is an area-based sample, in which grains of different sizes have an equal probability of being selected because all the grains within a predefined area are sampled. A grid-by-number (GbN; e.g. Wolman) sample of a particular sediment patch will always appear coarser than an equivalent area-by-number (AbN; e.g. photographic) sample. Ideally, comparisons between methods of grain-size measurement should be based on equivalent methods. In practice this may not be possible and one sample will need to be transformed to make it directly comparable with the other using the procedure developed by Kellerhals and Bray (1971). It should be noted that it is possible to undertake photographic grid-by-number sampling, thus obtaining a sample directly comparable with a Wolman sample, by either sampling on a grid laid over the photograph (although large numbers of images are likely to be required to get a sufficiently large sample size because the grid spacing must be twice the maximum grain diameter) or by measuring every grain, allocating them to size classes, and then summing the total area within each class (Sime and Ferguson 2003).

We have reanalyzed the grain-size data included in Figure 3a of Whitman et al. (2003) to illustrate the effect of correcting for the two problems introduced above. First, the proportion of grains in each conventional 0.5 φ (= $-\log_2$mm) sieve class were estimated from Figure 3a of Whitman et al. (2003) for both the Wolman and photographic samples, giving a Wolman grain-size distribution truncated at 8 mm (W_8) and photographic grain-size distribution truncated at 2 mm (Ph_2). A new photographic grain-size distribution (Ph_8), truncated at 8 mm, was then calculated. Figure 1 presents the grain-size distributions estimated from Whitman et al. (2003) (W_8 and Ph_2) and the recalculated photographic grain-size distribution truncated at 8 mm (Ph_8). The procedures of Kellerhals and Bray (1971) were then applied to transform the truncated photographic distribution (AbN; Ph_8) into a Wolman-equivalent distribution (GbN; $Ph_8 \rightarrow W_8$). The reverse transformation, to convert the Wolman distribution (GbN; W_8) into a photographic-equivalent distribution (AbN; $W_8 \rightarrow Ph_8$), was also applied.

Both sets of transformed data match their respective field equivalents fairly closely below about 25 mm (Figure 2). It is also apparent that the conversion from a grid-by-number to an area-by-number based sample (Wolman to photographic) appears to give a much better fit to the field data than the opposite conversion. This is because the transformation from areal- to grid-based data is very sensitive to small variations at the coarse end of the distribution as the transformed frequencies in each size class are proportional to the square of the grain size. A small change in the frequencies in large size classes results in large changes in the shape of the transformed cumulative grain-size curve. As an illustration of this sensitivity, consider the influence of a minor change to the coarse part of the distribution of the photographic grain-size distribution (Figure 3). Comparing the photographic grain-size distribution (Ph_8) and the same data after increasing by 1% the proportion of grains in the 32-45 mm and 45-64 mm classes and removing the equivalent 2% from the 64-90 mm class (Ph_{8X}), there is inevitably little change to the overall shape of the distribution curve (Figure 3a). However, this small change in the photographic grain-size distribution has a dramatic effect on the shape of the transformed grain-size distribution curve (Figure 3b). The modification has brought the transformed Wolman-equivalent distribution curve ($Ph_{8X} \rightarrow W_{8X}$) closer to the original Wolman grain-size distribution (W_8) compared with the same transformation without the modification ($Ph_8 \rightarrow W_8$). Thus, even a small bias at the coarse end of the photographically derived grain-size distribution can explain a significant amount of the difference observed between the grain-size distributions derived by photographic and Wolman sampling.

Although the match between the Wolman and photographic data is much improved by the Kellerhals and Bray (1971) transformation, it is worthwhile considering possible reasons for the remaining differences, particularly at the coarse end of the distributions. Contrary to the assertion of Whitman et al. (2003), and if the example they presented is typical, it appears that the photographic procedure produces distributions with a greater number of large grains than Wolman sampling.

Differences between the data may result from: (i) inappropriateness of the transformation procedure; (ii) random differences between samples; (iii) differences between the populations sampled; or (iv) bias in one or both of the sampling procedures. These possibilities are considered in turn.

While it is possible that the transformations applied are inappropriate for these data, this seems unlikely as they are well established. There is some controversy over the appropriate exponent to use when converting between subsurface (volumetric) and surface (grid or areal) samples (Kellerhals and Bray 1971; Diplas and Sutherland 1988; Fraccarollo and Marion 1995), but workers concur over the appropriate conversion factors between different types of surface sample (Diplas and Sutherland 1988).

It is also possible that the differences reflect random variations between samples collected by the two methods. Such variations are minimized by large sample sizes. Rice and Church (1996) estimated that sample percentile estimates may differ from the true population percentiles by between ±0.1 φ and ±0.25 φ (about ±7% to ±20% in mm) for a 400 grain Wolman sample. For the relatively small Wolman sample sizes employed by Whitman et al. (2003), random variations could account for much of the observed difference: the sample size may not be large enough to fully characterize the coarse tail of the grain-size distribution.

It is possible that the differences observed between the techniques reflect real differences between the sediments measured by the two techniques. Wolman samples are necessarily collected over relatively large areas, possibly resulting in the incorporation of several sedimentary units with different textural properties (Wolcott and Church 1991;

Buffington and Montgomery 1999), whilst the photographic approach characterizes grain sizes within small sample patches. To evaluate this, it would be necessary to observe the differences between the grain-size distributions collected at different sampling points within the area examined by Wolman sampling. Wolcott and Church (1991) demonstrated that the use of a stratified sampling strategy such as that deployed by Whitman et al. (2003), where one third of the photographs were collected at the thalweg and the remainder elsewhere, may introduce a systematic bias by failing to sample different sedimentary units in correct proportion to their prevalence on the river bed.

Finally, it is possible that there is a bias inherent within one or both of the sampling procedures. Wolman samples are known to be subject to operator bias, even when the operators are aware of such issues and take steps to avoid them (Marcus et al. 1995). However, operator bias is most likely when sampling very large or very small grains, and for the moderately sized particles sampled by Whitman et al. (2003) is unlikely to be particularly important. In the case of the photographic sampling, there may be a bias associated with the rejection of grains that were only partially visible or embedded in the photographs. This may result, for example, if there is a relation between grain size and embeddedness, which – in the experience of the present authors – there certainly is. There is also some bias, inherent in photographic techniques, associated with the inclination of individual grains relative to the plane of the image (leading to a reduction in their apparent size; Ibbeken and Schleyer 1986).

Whatever the causes of the difference, it is noteworthy that previous studies – that have rated photographic grain-measurement approaches against control data collected by directly comparable methods – have found a good correspondence between the two types of data (Adams 1979; Ibbeken and Schleyer 1986; Butler et al. 2001; Reid et al. 2001; Sime and Ferguson 2003). Most recently, using a fully automated procedure applied to digital photographs of exposed river gravels with a variety of lithologies, we have achieved a precision in percentile estimates of typically $<0.05\ \varphi$ for area-by-number samples (Graham et al. 2005a, b). This combined weight of evidence suggests that the differences observed in the data of Whitman et al. (2003) result from some methodological peculiarity in either the Wolman or photographic sampling procedures, rather than a general error in either photographic or Wolman approaches to grain-size measurement.

The non-invasive nature of photographic methods is particularly useful in monitoring applications. The potential to collect large numbers of samples quickly provides a means of characterizing spatial variations in substrate character over stream lengths that have previously been impractical. Photographic methods, especially adapted to work underwater as Whitman et al. (2003) propose, are therefore of great potential value and their contribution is valuable in this regard. Our analysis has emphasized the complexities of testing and utilizing such methods, and corrected some of the oversights of Whitman et al. (2003). Recent work has demonstrated that photographic methods can indeed provide information of high quality, achieving a precision equal to that of conventional methods, but in a fraction of the time (Graham et al. 2005b). Up-to-date and comprehensive treatments of issues related to grain-size measurement in gravel-bed rivers are provided by Bunte and Abt (2001) and Kondolf et al. (2003).

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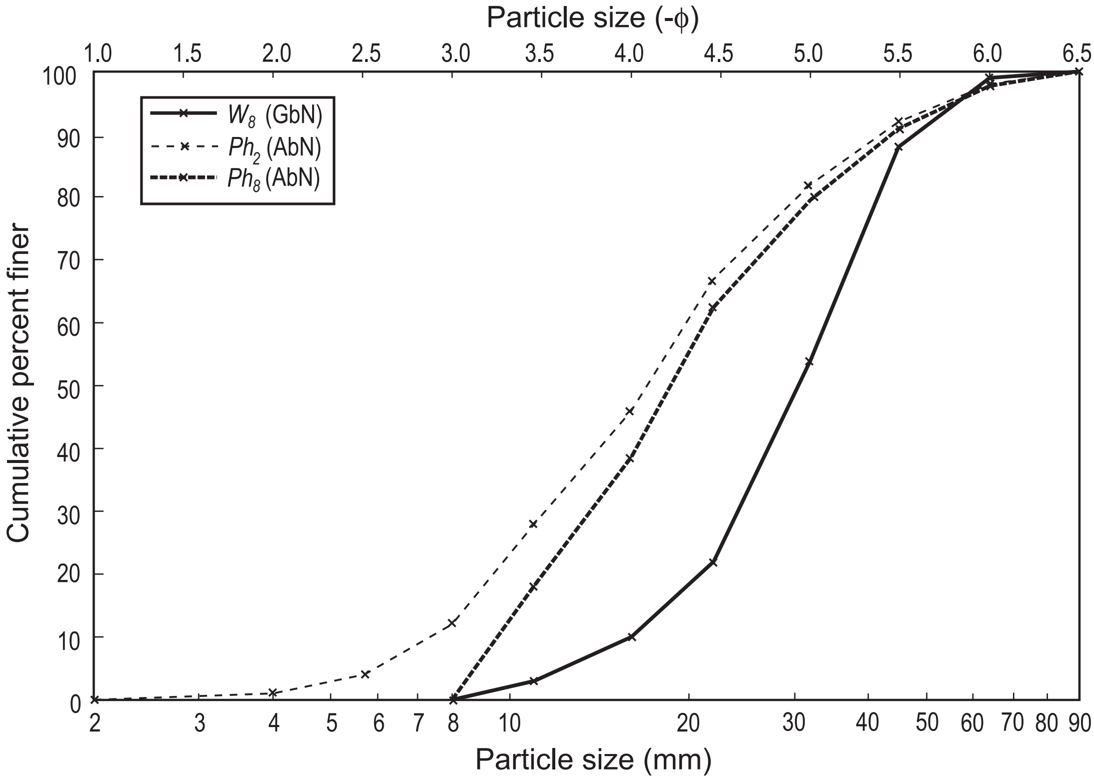

FIGURE 1.—Cumulative grain-size distribution curves presented by Whitman et al. (2003). The Wolman distribution (*W_8*) was truncated at 8 mm and the photographic distribution (*Ph_2*) at 2 mm. The photographic distribution has been recalculated here with an 8 mm truncation (*Ph_8*).

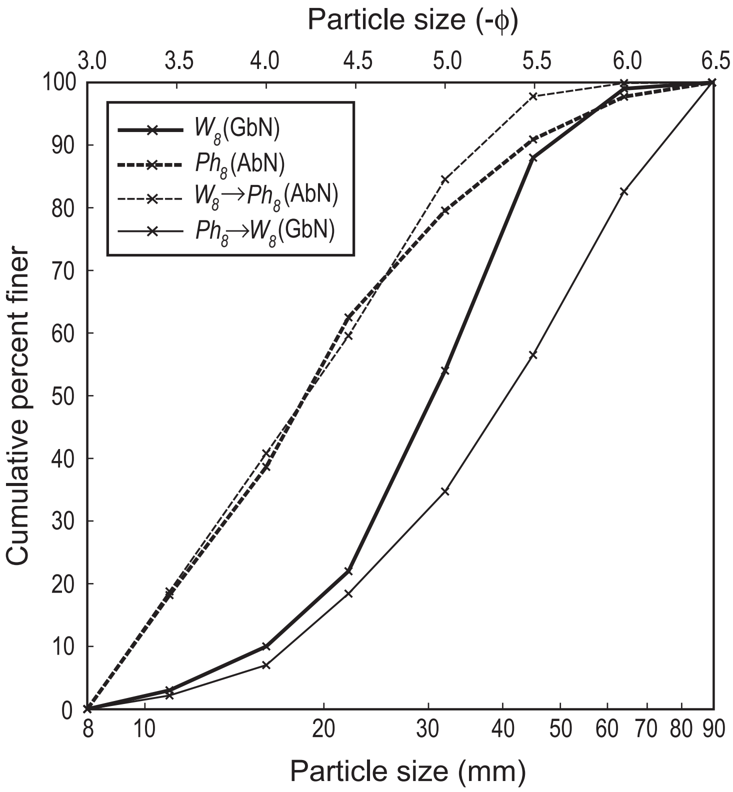

FIGURE 2.—The effect of applying a Kellerhals and Bray (1971) transformation to make the grid-by-number (GbN) Wolman distribution (W_8) equivalent to an area-by-number (AbN) photographic distribution ($W_8 \rightarrow Ph_8$) and the area-by-number (AbN) photographic distribution (Ph_8) equivalent to a grid-by-number (GbN) Wolman distribution ($Ph_8 \rightarrow W_8$).

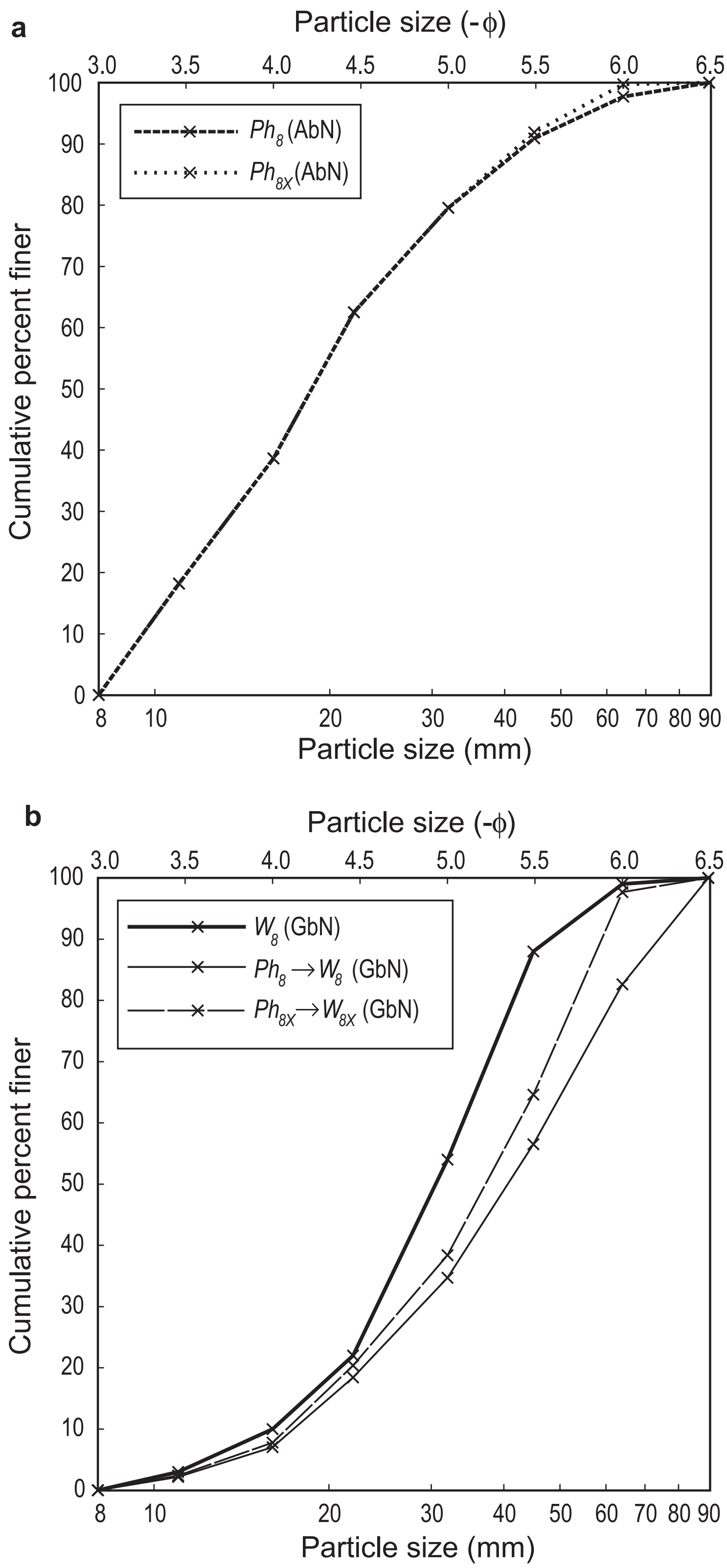

FIGURE 3.—An illustration of the sensitivity of the conversion from an areal to grid sample in the coarse part of the grain-size distribution. (a) The area-by-number (AbN) photographic distribution (Ph_8) and the same distribution modified by increasing the proportion of grains in the 32-45 mm and 45-64 mm classes by 1% (Ph_{8X}). The change makes little difference to the

shape of the distribution curve. (b) The effect of applying a Kellerhals and Bray (1971) transformation to the modified ($Ph8X \rightarrow W_{8X}$) and unmodified ($Ph_8 \rightarrow W_8$) photographic distributions to make them equivalent to a grid-by-number (GbN) Wolman sample. The original Wolman distribution (W_8) is shown for comparison.