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Chapter 9

Discussion and Conclusion

9.1 Overview

Throughout Parts II and III, the methods, results and interpretation were mixed together and detailed discussions were provided in § 4.7 and § 8.4. This chapter extends some of those more specific discussions by exploring the implications of the work presented in this thesis, discussing shortcomings and highlighting potential future improvements. Its purpose is to synthesise the work and point out the primary contributions. The chapter also attempts to bring these contributions full-circle, back to the original starting point and motivation for this work - physical habitat restoration for salmonids.

This thesis had two fundamentally methodological objectives. The first was to develop a technique for quantifying uncertainty associated with estimating geomorphological change from repeat topographic surveys (§ 1.3.1). The second was to develop a tool to make more meaningful mechanistic geomorphological interpretation of changes suggested by repeat topographic surveys (§ 1.3.2). In the case of the first objective, it was argued that existing methods that were were based on assumptions of spatially uniform surface representation uncertainties, require rethinking and further development. This is primarily because the magnitude of elevation changes experienced in fluvial settings is often of a similar magnitude to the magnitude of uncertainty about such changes. Thus, methods that do a better job of distinguishing the spatially variable nature of DEM uncertainty might allow better recovery of meaningful information about changes in some areas. These developments were laid out in Chapter 4 and their utility tested with application to four years of monitoring data from the braided River Feshie in Scotland. Out of this has come an easy to use DoD Uncertainty Analysis Software program, which allows inter-comparison of five different types of uncertainty analysis. On the basis of geomorphological plausibility, and minimising the loss of meaningful information from the DoD, the best performing uncertainty analysis (referred to as pathway 4) was one that provided a spatially variable estimate of surface representation using a fuzzy inference system and then updates that estimate, based on the spatial coherence of erosion and deposition units (see § 4.6 and § 4.7.1).

For the second objective, a simple but interpretively powerful set of masking tools was developed and used to extend the DoD Uncertainty Analysis Software program. These tools were geared to assist in making more meaningful interpretations of DoDs by capitalizing on the rich patterns of spatial change locked in DoDs. This was laid out methodologically in Chapter 5, but its utility was demonstrated in three contrasting monitoring applications in very different physiographic settings in Part III. Each case study told its own separate story, but collectively they demonstrated the utility of both the methodological contributions in a variety of monitoring applications.

9.2 DoD Uncertainty Discussion Extended to PHR

In Chapter 4, the problem of DoD uncertainty (the reliability problem) in morphological sediment budgeting was addressed from a fundamental research perspective. In that Chapter's discussion (§ 4.7) the emergence of a new preferred uncertainty analysis methodology was presented (§ 4.7.1); the question of why bother with uncertainty analysis was addressed (§ 4.7.1); the issue of interpolation errors was covered (§ 4.7.3); the application to other survey methods (§ 4.7.4) and the application to non-fluvial environments was considered (§ 4.7.5). Here, it useful to identify what some of the broader discussion points mean in a PHR or broader restoration monitoring context.

The significance of reliability uncertainties in the DoDs do not manifest themselves in a linear or uniform manner. Processes like shallow deposition tend to be more susceptible to minimum level of detection errors then processes like concentrated scour, which tend to be above typical detection limits. This susceptibility depends entirely on the styles and magnitudes of change (as represented by the shape of the elevation change distributions). That is, elevation change distributions that are normally distributed about no elevation change, versus those that exhibit a strong net aggradational versus net degradational skew will each be influenced by uncertainties in different ways. This makes it difficult to generalise about the significance of uncertainty and underscores the need for a robust, spatially variable estimate of uncertainty to be applied before any interpretation of a DoD should be made.

Another factor to consider that was not explored here is what can be said from highly uncertain, or poor quality, topographic data sets. All of the examples used in this thesis were from relatively high quality, high density, topographic surveys. Particularly in PHR, there are many situations where the available monitoring data may be of poorer quality, or have been collected for a different purpose. Yet, there still might be a need to try to make interpretations from this data. In theory, what should happen is that the DoD uncertainty analysis reveals whether or not anything can be said from the DoD (i.e. changes were of a magnitude greater than minimum levels of detection). As this is being done in a spatially variable manner, it is likely that such an analysis would permit interpretations and budget estimates of the largest scale changes in certain areas, but would simply reveal that no meaningful interpretation could be made from other large areas of the DoD. Using some lower quality datasets would be an appropriate test of the method.

The Mokelumne River (Chapter 7) provided a direct test of both methodological developments from this thesis in a PHR application. The case study showed that a wide range of basic questions relating to the construction process, ecological significance of change, and long-term monitoring could be addressed with the masking tools. However, the Mokelumne is a peculiar river in that it is so heavily regulated and there is so much restoration activity, it is difficult to get at the questions of the importance of *natural* system dynamics to fish. It would be informative to apply these methods to some more dynamic rivers that are experiencing more regular change post-restoration. It would also be worth more fully exploring some of the ecological masks in some non-restoration contexts.

9.3 Robustness of the Geomorphological Interpretation Mask

The suggestion that qualitative observations can be codified onto a map and a robust quantitative analysis can unfold from them will no doubt make some researchers uneasy. Geomorphology has fought hard to distance itself from its more descriptive and qualitative roots, such that as a discipline its practitioners have now grown skeptical of any analysis that can not be backed up by a consistently applied mathematical algorithm (Spedding 1997, Lane & Richards 1997). The reality is that the fluvial systems we study are complicated and whether we attempt to explain our observations and hypotheses about how they work with conceptual, empirical or mathematical models, we are forced to simplify and generalise.

There is certainly merit in deriving mathematical algorithms of landscape classification as they can be applied objectively and their results are repeatable. Particularly at the regional and catchment scale, DEM-based morphometric analysis has matured to the point that reliable landscape scale classifications can be robustly and consistently derived (Deng 2007, Marchi & Dalla Fontana 2005, Fisher *et al.* 2004). However, at the geomorphic unit scale that fluvial topographic monitoring attempts to resolve, morphometric analyses based on DEMs have yet to yield coherent classifications consistent with established geomorphological classifications. Part of the reason for this is scale, but an equally important factor is the lack of relief (relative to catchments) in fluvial settings and the difficulty in detrending DEMs. While banks may be easy to delineate on the basis of slope, or a channel may be simple to delineate in the presence of water, more detailed classifications are very difficult to derive automatically from a DEM. Another challenge is the stage-dependence of any fluvial classification. While fuzzy classification may offer a way around this, it does mean that 'repeatable' automated-classifications are tenable. Thus, manual classifications are typically resorted to. The geomorphological interpretation mask advocated here is no more subjective than applying the majority of sub-reach scale morphological or habitat classifications in the field (Thomson *et al.* 2001, Maddock 1999, Kondolf 1995, e.g.), or indeed performing geomorphological mapping (Parsons & Gilvear 2002, Taylor *et al.* 2000, Lewin 2001, e.g.).

It is important to be transparent about the fact that the geomorphological interpretation

FIGURE 9.1: An illustration of Gary Parker's rivers in flood analogy to the popular Far Side Cartoon. As direct observations of river beds during big floods are rarely ever actually made, we can only infer from observations before and after the flood the behaviour of river beds. Similarly, Parker argued that because we humans only ever see cows standing and walking on all four legs, we infer that they must always walk on four legs despite any direct observations the rest of the time. Far Side cartoon is © by Gary Larson, Associated Press and Andres McMeel Publishing and was reproduced from `http://msnbcmedia2.msn.com/j/msnbc/2080000/2080066.widec.jpg`.

is nothing more than an inference of likely mechanisms of change based on the available evidence. This partly comes down to the question of how do geomorphologists qualitatively make interpretations of observed changes in the field? We rarely have the luxury of being present during events that produce major changes (or if we are present, we do not have the equipment or means to safely measure the changes as they take place). At Gravel Bed Rivers VI, Parker *et al.* (2007) pointed out that we simply do not know what actually takes place on the bed of a river during the flood. Gary Parker made this point through the rather memorable analogy to a Gary Larson Far Side cartoon (Figure 9.1). With repeat topographic surveying, the problem is the same. We can only infer net changes by the differences we see between the observation windows (when the cows are on all fours). Whether we are interested in bedload transport rates or the composition of the bed during the flood (Parker *et al.* 2007, e.g.), or how the bed of a river changes in response to a flood (e.g. DoD); for all we know the cows could be standing in between. This is the crux of the compensation problem Lindsay & Ashmore (2002) identified, whereby successive cycles of erosion and deposition may be obscured by the overriding net result. This is an ongoing challenge for geomorphology, but it should not stop us from trying to make the most of the information we have. Thus, the geomorphological interpretation is only as robust as the practitioner's judgment and the quality of DoD and other evidence the interpretation was inferred from.

9.4 Future Developments

The DoD Uncertainty Analysis Software is currently written in Matlab, and requires a Matlab license and the Fuzzy Logic Toolbox to run. A platform independent, stand-alone application and an ArcGIS toolbar plug-in are currently under development. When completed, all three will be released as open source software under the GNU Public License. Users will be able to calibrate the rule systems according to their survey types and quality, and extend the rule systems according to the information they have at their disposal. This will give practitioners one way to exercise responsibility when analysing their DoD datasets by considering the reliability of their datasets. It is hoped that the tools will draw attention to the factors that lead to DEM uncertainty, thereby slowly improving data quality in the future. However, the real advantage will come in allowing practitioners to focus their efforts on making meaningful geomorphological interpretations of the data. For researchers, the Matlab code is probably the easiest place to quickly extend the methodology and build in improvements or bespoke modifications.

There are perhaps five future developments that will help test and refine these methods. The first and simplest is simply by applying the tools to as many datasets in different environments as possible (e.g. different fluvial environments as well as glacial, periglacial, hillslope, coastal, oceans, etc.). Hopefully, this will highlight any bugs, or areas where functionality should be added. This will be pursued organically by simply making the tools and code available. However, four other areas deserve some more focused research. These are a) using the tools on bigger, higher resolution datasets of different types over larger areas; b) improving and extending the DoD Uncertainty Analysis; c) closing the sediment budget, by incorporation of flux terms (sediment transport); and d) using the techniques to interrogate outputs from morphodynamic and LEM models.

9.4.1 Using Bigger, Mixed Datasets

If the last 10 years is any indication, in the next ten years the resolution and spatial extent of topographic surveys will increase dramatically. As Lane & Chandler (2003) observed, we are already 'dangerously close' to a convergence between the reductionist tendency for needing high resolution data sets and the generalist tendency for wanting to describe and study entire systems. It is predicted that through a variety of hybrid survey technologies, we will get what we asked for: incredibly high resolution topographic data (i.e. 100s to 1000s of points per square meter as opposed to 1 point per square meter) over entire catchments. When this happens, it is predicted that we will not be able to handle this data. Using the Feshie example, we already can (and have for 2006 and 2007) acquire c. 30-50 million points using terrestrial laser scanning in the same reach that we survey 30-50 thousand points by GPS (Brasington *et al.* 2007). It does not take any longer to acquire such data, but processing such data is another question. This thesis grew out of the observation that we are already at the point where we have more data then we know what to do with. For example, even GPS and total-station topographic data are not typically used to their fullest potential to make meaningful geomorphological interpretations. The methods developed here were an attempt to simply keep pace with the technology and make better use of the data we now have.

In the case of terrestrial laser scanning (TLS; a.k.a. ground-based LiDaR), Brasington *et al.* (2007) and Vericat *et al.* (2007) have already begun to reveal how the higher density and accuracy of laser-scanned data in the fluvial environment can extend what analyses can be made with just GPS or total station data. In 2007 and 2006, GPS and TLS surveys were run concurrently on the Feshie to allow a side-by-side comparison. A new technique for sub-sampling TLS data, so that high resolution DEMs can be constructed, was used to create DEMs from the TLS-data of equal resolutions to those DEMs created for GPS data (25 cm in this example). Figure 9.2 shows the difference between the DoDs from GPS and TLS surveys. Several striking patterns emerge, which reflect different abilities to distinguish real changes from noise in GPS and TLS survey data.

The first difference is that the TLS DoD is predicting significantly more erosion than the GPS DoD. When the GPS DoD is unthresholded, the TLS survey picks up roughly 37% more erosion, whereas when it is thresholded at a 95% confidence interval using a pathway 4 uncertainty analysis, it shows 78% more erosion.[1] In the thresholded GPS DoD (Figure 9.2B), a substantial fraction of low magnitude erosion is lost from the original GPS DoD (Figure 9.2A), due to the accuracy limitations of a GPS making it difficult to distinguish most low magnitude elevation changes from noise.

One of the things the uncertainty analysis gives rise to is this characteristic dip in the centre of the ECD (circle 1 in Figure 9.2) leaving behind a bimodal distribution. In § 4.6.5 the geomorphological plausibility of this ECD signature was discussed and it was postulated this was reasonable. Encouragingly, here the higher accuracy TLS data give some actual initial evidence that this ECD signature is probably real (circle 4 in Figure 9.2C). The TLS dip is not as pronounced, but this is probably due to a combination of the TLS data not having any uncertainty analysis applied here and the fact that the higher resolution data captures substantially more detail about low magnitude erosion changes. This is seen partly in circle 3 in Figure 9.2C, where substantial volumes of erosion from 5 to 50 cm are shown in the TLS ECD not picked up in the GPS DoDs. A preliminary DoD segregation using the masks derived in Chapter 8 suggest that most of these low magnitude changes are occurring over exposed bars (bar sculpting) and in areas of gravel sheet deposition (not reported here). Changes at this scale simply can not be resolved from the GPS surveys.

Another area where the TLS data picked up significantly more volume of erosion was in high magnitude erosion areas (e.g. >1.25 m). This is shown in circle 2 in Figure 9.2C,and a preliminary assessment using the geomorphological interpretation masks used before shows that this volume is almost entirely in areas experiencing bank erosion. This is a confirmation that a) the over-generalisation of bank morphologies in the GPS surveys leads to interpolation errors

[1]It should be noted that the TLS data has no uncertainty analysis applied here (an area of future development). However, the TLS data is also of much higher resolution and accuracy.

that mask significant volumes of erosion, and b) that the specification of higher magnitude minimum levels of detection in such areas is reasonable.

On the deposition side, there is less divergence the GPS DoDs and TLS DoDs. In fact, the TLS data actually shows about 6% less volume of deposition then the unthresholded GPS DoD. This is a reflection of the fact that the unthresholded GPS DoD is sugesting large volumes of low magnitude deposition that actually can not be resolved from noise. The pathway 4 analysis addresses this sensibly, but from the thresholded GPS to the TLS DoD there is a 22% discrepancy. As with the low magnitude erosion, this is probably partly real (reflecting the better ability of the TLS data to detect such changes) and partly because the TLS data has not had an uncertainty analysis applied.[2]

In many respects, a field of 'virtual surveying' (p. comm, S. Ramsey, Leica Geosystems, 2007) is likely to emerge whereby our datasets are so rich, that they are actually every bit as complicated as the real world. We may be able to capture the datasets much more rapidly, and over entire system scales. However, it will still take time to explore such datasets, just like it takes time to explore the real landscapes they represent and make meaningful interpretations from them. These datasets will require new ways to mine data, and use the data sensibly and efficiently to draw out meaningful generalisations, interpretations and conclusions. It is speculated that the geomorphological community will have to be careful not to become too obsessed in applying brute-force solutions with these new über-datasets to the basic *geomorphological* questions that should really drive the discipline. The über-datasets will undoubtedly open up new avenues of research, but it is argued that caution and skill should be exercised to use this data creatively to address interesting geomorphological questions. The pervasiveness of the 'survey it because we can' philosophy (§ 3.3.1.1) is analogous to the post-depression era mentality of stashing away and saving everything they could get their hands on. Analogous to those who grew up in those eras, today's geomorphologists have largely grown up in a fundamentally data-poor environment. While war-chests of data may now be forming and ultimately serve worthwhile means, the resulting data-rich environment may not necessarily reveal geomorphological insights that are fundamentally any better without thoughtful and deliberate methodological development on the analysis side.

More work needs to be undertaken to extend the DoD Uncertainty Analysis Software and methods to deal with TLS data. However, as eluded to above a preliminary assessment of the TLS data seems to suggest this should be a tractable and fruitful extension.

9.4.2 Improving and Extending the DoD Uncertainty Analysis

There are may ways in which the DoD uncertainty analysis might be tweaked and extended to offer some gains. Extending the applicability of the analysis to survey data from LiDAR, TLS and aerial photogrammetry is an obvious area that needs attention. As the fuzzy inference

[2]Note, a manuscript in preparation by Brasington, Vericat and Wheaton addresses the estimation of DoD uncertainty for TLS data, but is beyond the scope of this thesis.

system (FIS) backbone of the approach is so flexible in its implementation, this should be largely straight-forward. However, beyond those simple extensions there are at least three possible areas to consider that might improve the overall quality of the uncertainty estimate:

1. Instead of applying a binary threshold to the DoDs, apply a weighted threshold
2. Incorporate roughness explicitly into FIS
3. Use more repeat surveys to calibrate fuzzy membership functions and error models

In this context, an *improved* quality of uncertainty estimate might be beneficial insofar as allowing further recovery of elevation change predictions, which can be distinguished from noise.

The idea of a weighted threshold was proposed previously by Lane *et al.* (2003, p.252) but its application has not been reported. Essentially, this could be used as an alternative to a confidence interval defined threshold that throws away all information beneath a certain threshold. Instead, the full probability distribution of t statistic test could be used to weight DoD predictions on a cell by cell basis. Additionally, it might also be possible to make more use of the final output membership functions of elevation uncertainty for each cell instead of just using the defuzzified value to construct a probability distribution.

The incorporation of surface roughness into the FIS would be a significant improvement to overall elevation uncertainty estimates. It would allow a direct consideration of the influence of grain roughness and vegetation, which obviously blur topographic boundaries. In the case of TLS data, a direct measure of roughness may be possible (Vericat *et al.* 2007). Otherwise, facies maps related empirically to roughness heights may be a tractable alternative for other survey techniques. Appendix E revealed that roughness retrieval from GPS and total station topographic data at the resolutions it is currently collected at is inadequate to reliably reconstruct roughness.

In individual applications of the DoD uncertainty analysis, the quality of predictions could always be improved by performing repeat surveys of sub-areas of the study site within a short period of time (e.g. hours or day) when the topography was known not to have changed (e.g. § 4.3.1.4). This could be used to better calibrate the input and output fuzzy membership functions in the FIS to a specific site. However, the additional cost in surveying time and analysis should be weighed up against the potential gains.

With all of the above attempts, it should be remembered that these will do nothing to improve the quality or accuracy of the topographic survey data itself. These are simply attempts to glean more information from that data. Only improvements in the surveying itself (e.g. point resolution and sampling pattern) or the surveying technology (e.g. TLS) may improve the accuracy of such data. Given the inherent roughness and noise of fluvial surfaces, it is unlikely that higher precision point data from better instruments (e.g. higher than TLS or total stations) are necessary nor would they significantly improve overall surface representation accuracy. Arguably, the goal should not be to reduce the uncertainty, but rather to have a better understanding of the magnitude of that uncertainty so that the data can be used to make more reliable statements.

9.4.3 Closing the Sediment Budget

The storage terms in the sediment budget are the low fruit. These are the terms that can be readily estimated from net change in DoD analysis like those presented in this thesis. Although the thesis went to great lengths to demonstrate and evaluate the robustness of the nuances of the approach to working with DoD uncertainties, it should be highlighted that the resulting methodology is very simple to apply. It only requires a raw x,y,z topographic point cloud as an input, from which the DEM, a point density grid and a slope analysis can all be derived. Thus, more needs to be done to completely close the sediment budget (probably at event time-scales initially), by incorporating direct measurements of sediment transport fluxes. It remains unknown what percentage of the sediment budget the storage terms represent, in relationship to the total volume of sediment passing into, through and out of the system. Coupling direct flux measurements with some of the masking techniques developed here, could be a potent combination for better understanding the kinematics behind mechanisms of channel change. This type of information is not only essential to better understanding the sediment transfer processes that shape fluvial environments (Pyrce & Ashmore 2005, Pyrce & Ashmore 2003), but also critical to the development of realistic morphodynamic and landscape evolution models.

9.4.4 Modelling the Morphodynamics

Morphodynamic and landscape evolution models both take digital evolution models as their initial condition and produce new digital elevation models as their primary output (Coulthard 2001). As such, both suffer from the same problems that are encountered in DoD analysis: they produce impressive visualisations, but how do you quantitatively interpret the changes represented (Martin & Church 2004, Cao & Carling 2002*b*, Cao & Carling 2002*a*). Applying the simple masking techniques proposed here could provide a simple and direct means of more quantitatively interrogating such datasets. In the case of morphodynamic models that are running at contemporary time-scales and emulating processes that are measured by repeat topographic surveys, the DoD masking tools could be used to validate and calibrate models. The elevation change distributions could be used to see if a model is producing similar signatures of change, and the masks could be used to segregate the changes by the processes in the model. These could be compared directly against inferred mechanisms of change from field data to look for agreement and discrepancies. There are a wealth of opportunities combining repeat topographic datasets from both field data and model simulations, that are waiting to be explored.

9.5 Revisiting Broader Uncertainty Context

This thesis set out with an aim of addressing two types of uncertainties associated with monitoring topographic change in rivers: a *reliability* uncertainty and a *structural* uncertainty. The reliability of topographic data and derived DEMs was addressed through the DoD Uncertainty Analysis development (Chapter 4). The *structural* uncertainty of how to make more meaningful geomorphological interpretations of DoDs was addressed through the development and deployment of masking tools (Chapter 5). However, Chapter 2 laid out a broader context for uncertainty that has not been explicitly revisited since Part I. Here, that context is returned to, briefly, in order to bring closure to the thesis.

Chapter 2 laid out a lexicon for uncertainty and a typology for uncertainty, both of which acted to recast knowledge about uncertainty as useful information as opposed to something to be avoided. In the Van Asselt & Rotmans (2002) uncertainty typology, all uncertainty is derived from two sources: *natural variability* and limited knowledge. Both the reliability and structural uncertainty addressed in this thesis are due to *limited knowledge*. A wide range of tools used to communicate uncertainty in the sciences were reviewed in Chapter 2. From these, the DoD uncertainty analysis methodological development in this thesis drew on a mix of fuzzy, probabilistic and Bayesian inference techniques to quantify and represent unreliability uncertainties. However, the masking was an attempt to address the more fundamental *structural* uncertainty of *reducible ignorance*. Unlike *unreliability* uncertainties, which have a wide range of scientific tools to help quantify them, *structural* uncertainties are not necessarily quantifiable. Thus, an uncertainty like *reducible ignorance* can be addressed through further research or new analyses. In the case of this thesis, the new analyses were simple spatial masks that had not been used in this way before. By addressing this *reducible ignorance*, uncertainty was constrained, but not eliminated. More accurately, most of this *reducible ignorance* has now become an *unreliability* uncertainty (arguably of little significance). The *unreliabilities* come about in the inaccuracies of the classification process. However, some of the *reducible ignorance* may have been converted to *conflicting evidence* as and when different geomorphologists might use slightly different classifications for masking or have different inferences about the mechanisms of change.

The last part of Chapter 2 addressed different philosophical approaches to uncertainty ranging from ignoring it to embracing it. It was argued that efforts to reduce *all* uncertainty were unrealistic and when uncertainty is viewed as useful information embracing uncertainty is the most tractable and most powerful approach. As mentioned in § 9.4.2, the thesis never set out to reduce all uncertainty, but rather to acquire a better handle on how uncertainties that exist can be used to make better geomorphological interpretations.

9.6 Thesis Conclusions

The use of repeat topographic surveys to monitor geomorphological change in rivers (morphological sediment budgeting) is becoming a readily available standard of practice in both basic fluvial geomorphological research, and river basin management activities like physical habitat restoration. This is thanks to advances in surveying technology and GIS analysis software, that now offer a rich and relatively affordable range of alternatives to collecting such data and performing analyses like DEM differencing. However, with these new tools come questions about the reliability of the analyses and what they mean. The reliability question specifically concerns unreliability uncertainties due to limited knowledge, while the meaning question concerns structural uncertainties due to limited knowledge.

The reliability question has received a reasonable amount of attention in the literature (Lane *et al.* 1994, Lane *et al.* 2003, Brasington *et al.* 2000, Brasington *et al.* 2003), but still rather simplistic spatially uniform estimates of uncertainty have emerged from such research. These tend to underestimate the magnitude of uncertainty in some areas and overestimate it in others. This thesis has presented a new method, which extends past work by providing a means to flexibly estimate surface representation uncertainties in individual DEMs in a spatially variable manner. This was achieved by means of a fuzzy inference system, which as presented can be performed on any raw topographic survey point data with some calibration. Its real strength is that it can easily be extended and improved to incorporate other types of information, as and if it is available, which are known to contribute to surface representation uncertainty (e.g. roughness, individual point quality metrics, surface composition, etc.). Individual estimates of surface representation uncertainty are calculated independently for DEMs used in a DoD. This means that different types of surveys and information can be used to come up with the best available estimate of uncertainty. These estimates are then propagated through to the DoD, and converted to a probabilistic estimate of uncertainty in the DoD. This estimate can be improved and updated, using Bayes theorem, based on an analysis of the spatial coherence of erosion and deposition units within the DoD. The resulting probabilistic estimate of DoD uncertainty reflects not just the spatial variability, but also the spatial structure. These analysis tools, along with their predecessors, were packaged in a wizard-driven DoD Uncertainty Analysis software application.

Although the geomorphological meaning and interpretation questions are what originally motivated the development of morphological sediment budgeting techniques from repeat topographic surveys, these topics have been largely forgotten in the literature while the reliability question has dominated. This thesis attempted to return some focus to this more fundamental question by developing some simple masking tools to allow the flexible segregation of the DoD budget. A range of masking tools were proposed, including some based off of standard geomorphological and habitat classifications, a classification of difference technique, a geomorphological interpretation mask, and some ecologically relevant masks. The mask units themselves are generally at bar-scale resolutions, but their collective classification is carried out over the entire DEM domain (generally reach scale). Whether applied in parallel or individually, the masks aid in spatially and quantitatively segregating the budget in a manner that allows a more mechanistic explanation of the changes recorded by a DoD. No single mask is universally applicable, and mask definition, importantly, is strongly dependent on the judgment and interpretation of the user performing the analysis. Thus the tool can be used in different ways on the same DoD datasets, to come up with alternative explanations or to quantitatively test competing hypotheses. This is significant because the tool itself does not point toward any particular interpretation, and it leaves such debates where they belong, between geomorphologists. What it allows instead is a quantitative interrogation of these rich spatial datasets and their patterns, over the qualitative interpretations of reach-scale maps that have been used to date.

The utility of both these methodological developments was explored using three different monitoring data sets representing event-based monitoring (Sulphur Creek, California), restoration monitoring (Mokelumne River, California), and annual-monitoring of a natural dynamic system (River Feshie, Scotland). One of the themes that emerges across these applications is the sharp contrast between areally extensive mechanisms of change versus the most volumetrically efficient. Interestingly, those mechanisms of geomorphological change which take up the most space (aerially) are not necessarily those responsible for the greatest volume of net change. An example of this is the contrast between bar development and bank erosion. Bar development occurs over large areas and can visually dominate a reach, but tends to consist of relatively shallow deposition. By contrast, bank erosion may only carve a visually obscure sliver off the channel margins, but due to the height of the banks may account for a substantial volume of erosion. The comparison of volumetric and areal elevation change distributions helps disentangle these characteristics, whereas the masking can help identify the dominant mechanisms of change.

In conclusion, some new tools have emerged from this thesis that extend what can reliably be inferred about geomorphological change from repeat topographic surveys. These tools do not themselves improve the reliability of the data, but they do allow reliability to be assessed objectively and help determine what can and can not be gleaned from DoDs.

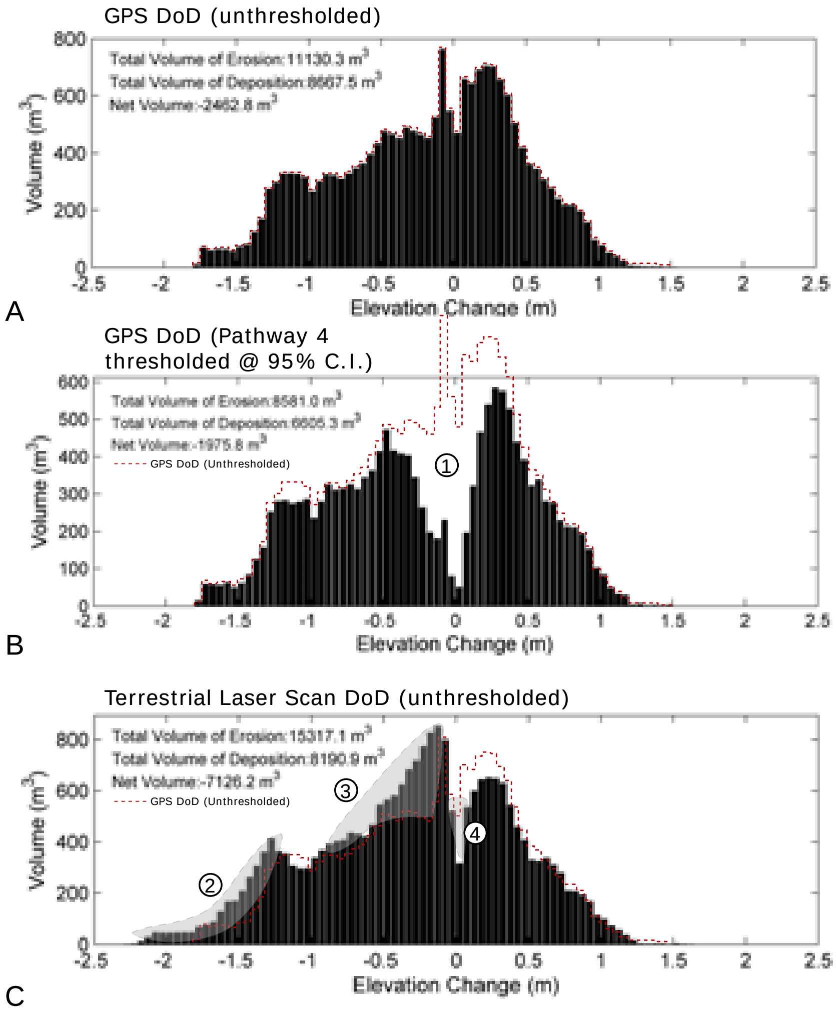

FIGURE 9.2: A comparison of DoD elevation change distributions derived from a GPS survey and a concurrent terrestrial laser scan survey on the Feshie from 2007 to 2006. A) The unthresholded DoD from GPS surveys with no accounting for uncertainty. B) The DoD from GPS surveys with a pathway 4 uncertainty analysis applied and thresholded at a 95% confidence interval. C) An unthresholded DoD from terrestrial laser scan surveys. The dashed-red linke represents the outline of the unthrsholded GPS DoD and is scaled accordingly in B) and C). The numbered circles and corresponding shaded areas are referred to in the text. Note the DEM resolution in A & C was 25 cm, whereas B was 1 m.